

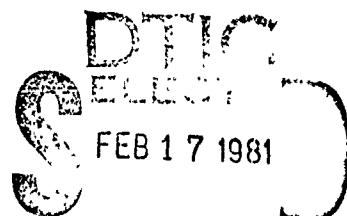
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NAVAL POSTGRADUATE SCHOOL

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THESIS

NUMERICAL OPTIMIZATION USING DESKTOP COMPUTERS

by

Walter Bacon Cole

September 1980

Thesis Advisors:

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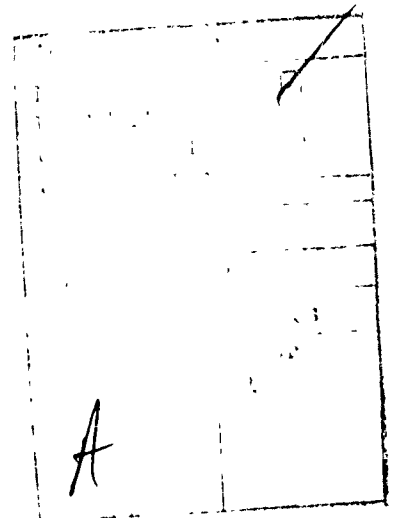
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Numerical Optimization Using Desktop Computers

by

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Lieutenant, United States Navy
B.S.M.E., Purdue University, 1974

Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

Two computer programs were developed in advanced BASIC to perform numerical optimization of a user supplied design problem on the Hewlett Packard 9845A desktop computer. An executive program, OPCON, provides the interactive link between the computer user and the DESOP numerical optimization program. DESOP performs the numerical optimization using the sequential unconstrained minimization technique with an external penalty function. The unconstrained subproblem is solved using the Fletcher-Reeves method of conjugate directions, and using Golden Section search and polynomial interpolation in the one-dimensional search.

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NOMENCLATURE

English Letter Symbols

A_r	- Solar collector receiver surface area
A_t	- One half the solar collector aperture area
B	- Cantilevered beam width
C_d	- Solar collector depth
C_p	- Specific heat
CR	- Solar collector concentration ratio
E	- Young's modulus of elasticity, or the penalty function exponent used in DESOP
F_1	- Lower Golden Section fraction
F_2	- Upper Golden Section fraction
H	- Cantilevered beam height
\bar{H}	- Equality constraint vector
I_{calc}	- A user's flag in the DESOP program for initial and final user generated output
L	- Cantilevered beam length, or the solar collector length
\dot{m}	- Solar collector mass flow rate
M_{fr}	- Solar collector mass flow rate
N_{dv}	- Number of design variables
Obj	- Objective function
Opj	- Penalized objective function
P	- Cantilevered beam load
Q_a	- Solar collector heat available

Q_u	- Solar collector heat gain
Q_y	- Yearly solar collector heat available
q_i	- Heat flux
R	- Penalty parameter used in DESOP or the solar collector receiver radius
r	- Solar collector receiver radius
T_{ap}	- Solar collector aperture cover temperature
T_{c2}	- Solar collector coolant exit temperature
θ_{tai}	- Solar collector acceptance half angle
θ_{tat}	- Solar collector truncation angle
t	- Solar collector distance between the reflector and a point tangent to the receiver
V	- Cantilevered beam volume
x	- Solar collector reflector coordinate
\bar{x}	- Design variable vector
y	- Solar collector reflector coordinate

Greek Letter Symbols

α	- One-dimensional search move parameter
δ	- Cantilevered beam deflection
θ	- Solar collector geometry angle measured from the collector centerline (See Fig. 6)
θ_i	- Solar collector acceptance half angle
θ_t	- Solar collector truncation angle
v	- Cantilevered beam shear stress
σ_b	- Cantilevered beam bending stress

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I. INTRODUCTION

A. BACKGROUND

Most engineering design problems contain several continuous variables and as such have an infinite number of solutions. The purpose of optimization is to find the best possible solution among the many potential solutions for a given problem in terms of some effectiveness or performance criteria. There are several methods of optimization. The methods may be classified as follows:

Analytical methods which use the classical techniques of differential calculus and the calculus of variations.

Numerical methods which use past information to generate better solutions to the optimization problem by means of iterative procedures. Numerical methods can be used to solve problems that cannot be solved analytically.

Graphical methods which use the preparation of a plot of the parameter to be optimized as a function of one or more variables. This method although simple and easy to use becomes unmanageable when there are three or more design variables.

Experimental methods which use direct experimentation of the actual process, the results of one experiment being used to decide on where to perform the next experiment.

Case study methods which evaluate the results from a number of representative cases, and choose the "best" solution. The "best" solution is thus not likely to be the optimum solution.

Of the optimization methods, the numerical method lends itself to computerized solution. As design is an interactive process between the designer and the problem, and the desktop computer lends itself towards dedicated interactive use, the development of a numerical optimization program for use on a desktop computer in an interactive mode, is the objective of this thesis.

To date a great amount of effort has been spent developing reliable and efficient optimization programs for mainframe computers. These programs are fairly large and complex, requiring a substantial amount of core space during execution. The size and complexity of the programs has been the result of an attempt to minimize the amount of computer time required to perform an optimization and thus the cost to the user. With the advent and availability of desktop computers, there has been a sharp reduction in the cost of computer time to the computer user. While the desktop computer has far less core space than a mainframe computer, once the time factor is removed from the numerical optimization process it is possible to put a small but reliable numerical optimization program on a desktop computer. A design problem concerning the optimal geometry

for a nonimaging parabolic trough solar collector was developed to demonstrate the engineering application of the numerical optimization program developed for this thesis.

B. SCOPE

The numerical optimization of a given function may be accomplished using many varied and different algorithms. Some of the more popular methods used are: random search, linear programming, feasible directions, Golden Section, Newton's method and sequential unconstrained minimization. A particular optimization program will use one or more of these methods to efficiently and reliably arrive at the best solution to a particular problem.

For this thesis two computer programs were developed to perform numerical optimization on a desktop computer. The first program was developed as an executive program to control the optimization process. The executive program is named OPCON which stands for Optimizer Control program. OPCON provides the interactive link between the user and the program which performs the numerical optimization. OPCON allows the user to input data, attach a specified analysis subprogram to the numerical optimization program and control execution of the numerical optimization program. The second program developed was the numerical optimization program, DESOP. DESOP stands for Desktop Sequential unconstrained minimization technique Optimization Program.

DESOP performs the numerical optimization of the user supplied problem using the sequential unconstrained minimization technique with an external penalty function. The unconstrained subproblem is solved using the Fletcher-Reeves method of conjugate directions, Golden Section search, and polynomial interpolation.

The third computer program, NISCO, was developed to model a nonimaging concentrating compound parabolic trough solar collector using thermophysical, geophysical, optical and economic analysis to compute a life-cycle cost for a design with a stated energy capacity. NISCO stands for NonImaging concentrating compound parabolic trough Solar Collector.

C. OBJECTIVE

The objective of this thesis was to develop a system of interactive programs for the Hewlett-Packard 9845A desktop computer which perform numerical optimization, and to demonstrate the capability on the design of a nonimaging concentrating compound parabolic trough solar collector. Three programs were developed to meet the objective: an executive program, a numerical optimization program and a solar collector analysis program.

The purposes of the executive program OPCON are:

1. To provide a primary point of contact for the computer user from which to effect a numerical optimization on any number of user prepared analysis subprograms.

2. To provide a standardized, formatted input for the design variables, side constraints and optimizer control parameters, which is recognizable by all the programs in the numerical optimization package of programs.

3. To control the operation of the different optimization and design analysis programs within the system through a process of program overlays which maximizes the computer space available for the design analysis program.

4. To develop a program which is portable to different computers using an advanced BASIC language.

The purposes of the numerical optimization program DESOP are to develop an optimization program that:

1. Is reliable in reaching a design optimum, irrespective of the starting point.

2. Will arrive near the design optimum using default values for the optimizer control variables.

3. Will allow the user to monitor the optimization process and to change the optimizer control variables to more efficiently and/or more accurately reach the design optimum.

4. Is portable to different computers using an advanced BASIC language.

The purposes of the solar collector program NISCO are to:

1. Model a nonimaging concentrating compound parabolic trough solar collector using a system of thermophysical, geophysical, optical and economic equations.

2. Arrive at an optimum design for a solar collector given a stated average daily heat gain and a life-cycle period.

II. NUMERICAL OPTIMIZATION

A. THE CONCEPT OF NUMERICAL OPTIMIZATION

Consider the problem of designing the cantilevered beam shown in Figure 1. The design task may be broken down into three major parts. First, the objective of the design must be determined, which in this case is to minimize the weight of the beam required to support the concentrated tip load P . Second, any physical constraints that may effect the design must be determined. Thirdly, any limits which exist on the design variables must be determined. The design problem may then be reduced to a system of equations as follows:

Minimize the volume (V)

$$V = B \cdot H \cdot L$$

Subject to:

Bending stress (σ_b)

$$\sigma_b = \frac{6 \cdot P \cdot L}{B \cdot H^2} \leq 20000 \text{ psi}$$

Shear stress (v)

$$v = \frac{3 \cdot P}{2 \cdot B \cdot H} \leq 10000 \text{ psi}$$

Deflection under load (δ)

$$\delta = \frac{4 \cdot P \cdot L^3}{E \cdot B \cdot H^3} \leq 1 \text{ inch}$$

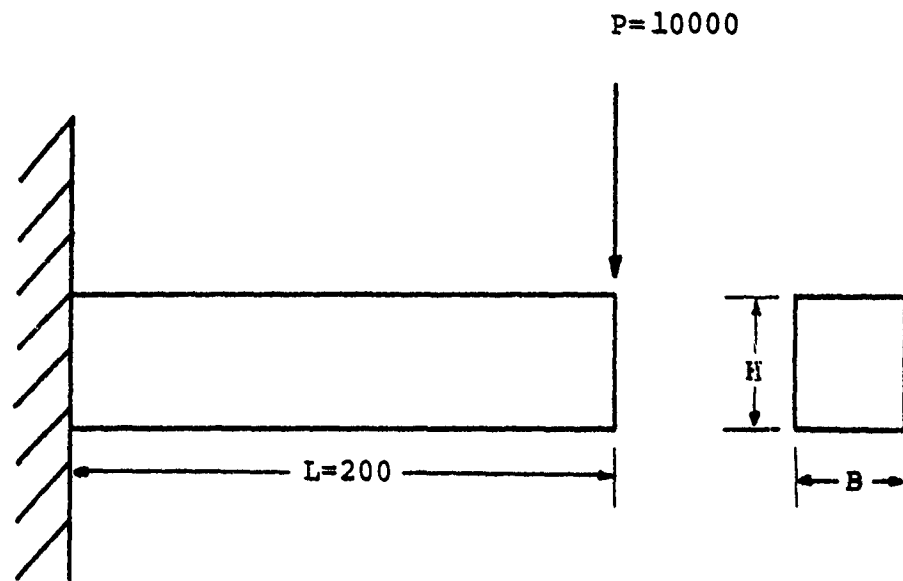


Figure 1. Cantilevered Beam Design Problem

With geometric constraints such that:

$$0.5 \leq B \leq 0.5$$

$$1.0 \leq H \leq 20.0$$

$$H/B \leq 10.0$$

At this time the following definitions are introduced:

Objective Function - The parameter which is to be minimized or maximized during optimization. The objective function always occurs on the left side of the equation unless it is also used as a design variable. An objective function may be either linear or nonlinear, implicit or explicit, but must be a function of the design variables.

Design Variable - Any parameter which the optimization process is allowed to change in order to improve the design. Design variables appear only on the right hand side of equations in the analysis program.

Inequality Constraint - Any parameter which must not exceed specified bounds for the design to be acceptable. Constraint functions always appear on the left side of equations. A constraint may be linear, nonlinear, implicit or explicit, but must be a function of one or more design variables.

Equality Constraint - Any parameter which must equal a specified value for the design to be acceptable. The same rules apply to equality constraints as inequality constraints.

Side Constraint - Any upper or lower bound placed upon a design variable. Side constraints are usually not included in the system of equations that comprise an analysis program. Instead they are usually included as part of the data input to the optimization program.

Analysis Code - The system of equations utilizing the design variables which are used to calculate the objective function and the constraints of a particular design problem.

The general optimization problem may thus be stated mathematically as:

Find the set of design variables \bar{X}_i where $i = 1, 2, \dots, n$ which will:

Minimize the objective function (Obj)

$$\text{Obj} = f(\bar{X})$$

Subject to:

Inequality constraints (G)

$$G_j(\bar{X}) \leq 0 \quad j = 1, 2, \dots, m$$

Equality constraints (H)

$$H_j(\bar{X}) = 0 \quad j = 1, 2, \dots, l$$

Side constraints

$$x_i^l \leq x_i \leq x_i^u \quad i = 1, 2, \dots, n$$

Returning to the cantilevered beam problem, it may be stated in the standard format as follows:

Let $X(1) = B$, $X(2) = H$, and $\text{Obj} = \text{Vol} = B \cdot H \cdot L$

Then minimize $\text{Obj} = \text{Vol}$

Subject to:

$$G(1) = \frac{\sigma_b}{20000} - 1 \leq 0$$

$$G(2) = \frac{v}{10000} - 1 \leq 0$$

$$G(3) = \delta - 1 \leq 0$$

$$G(4) = \frac{H}{B} - 10 \leq 0$$

With side constraints:

$$X(1)^l = 0.5$$

$$X(1)^u = 5.0$$

$$X(2)^l = 1.0$$

$$X(2)^u = 20.0$$

It is thus fairly simple and straightforward to perform an analysis on a particular beam for a given B and H. Successive analyses may be performed on the cantilevered beam by solving the above system of equations. It is desirable to automate the successive solutions and to direct the solutions such that each solution is a better design than the last. One approach for doing so, and the one used by DESOP is to proceed as follows: Start with initial values for B and H. Solve the above set of equations to find the objective function Obj and to see if any constraints are violated. A pseudo objective function is created to represent designs when constraints are violated. If a constraint is violated, a penalty is added to Obj to form a penalized objective function Opj. The gradient of the

penalized objective function at the initial design may be found by taking the first partial derivative of Op_j with respect to the design variables. The gradient of the penalized objective function defines the direction of steepest ascent. In the case of the cantilevered beam, it is desired to minimize the objective function; therefore, the greatest improvement in design may be achieved by moving in the negative gradient, or steepest descent direction. From the initial design point a search is performed in the steepest descent direction for the minimum value of Op_j in that direction. At the new minimum, the gradient of the penalized objective function is again determined and a search is performed in a conjugate direction until a second minimum is found. Successive iterations are performed until the gradient is found to be zero or each successive iteration produces a sufficiently small change in Op_j such that for all practical purposes the minimum has been found. At this time the penalty function is increased. If the design is in a region where there are no constraints violated an increase in the penalty function will not change the value of Op_j . If on the other hand the design is in an infeasible region where there are one or more constraints violated, Op_j will be increased, and the search for a new minimum will commence. If the minimum of the objective function exists in the infeasible region,

the minimum value for the objective function in the feasible region will be approached from the infeasible region as the penalty function is increased. The design improvement process will terminate when a zero gradient is found or successive iterations produce a sufficiently small change in the value of Opj and an increase in the penalty function causes no change in Opj .

The minimum thus reached by the optimization process is a minimum with respect to the penalized objective surface immediately surrounding the final design point. The optimization process cannot distinguish between local and global minimum points. It is thus good engineering practice to run several optimizations for a particular design problem from several different initial design points. If optimizations performed from different initial design points converge on the same minimum point, that point is probably a global minimum. If on the other hand two or more minimums are found, there may be local minimums located in the design space being considered and care must be taken to find the global minimum.

B. THE DESOP NUMERICAL OPTIMIZATION PROGRAM

The DEsktop Sequential unconstrained minimization technique Optimization Program was developed using the basic optimization approach outlined in Section II.A. A copy of the program is included in Appendix E. The major

program structure is shown in Figure 2. The following discussion will refer to Figure 2 and describe the major features of the program.

1. Basic Program Execution

The DESOP program begins execution when it is loaded, linked to the user's analysis subprogram, and the program is instructed to run by the OPCON program. The above actions are automatically performed by the OPCON program. DESOP is loaded into the computer by an overlay process. Therefore no variables can be directly transferred between the DESOP and OPCON programs. DESOP begins execution by reading the optimizer control variables and the design variables that were input using the OPCON program and saved to a mass storage device. The program then sets Icalc equal to one and evaluates the objective function and constraints at the initial design point. Icalc is a flag provided the user to key user specified output on the initial and final design analysis. DESOP will provide the user with a hard copy output of the initial design variables, the value of the constraints, the objective function and the penalized objective function. The user then has the option of continuing with the DESOP program to optimize his analysis subprogram or to return to the OPCON program to change one or more of the input parameters.

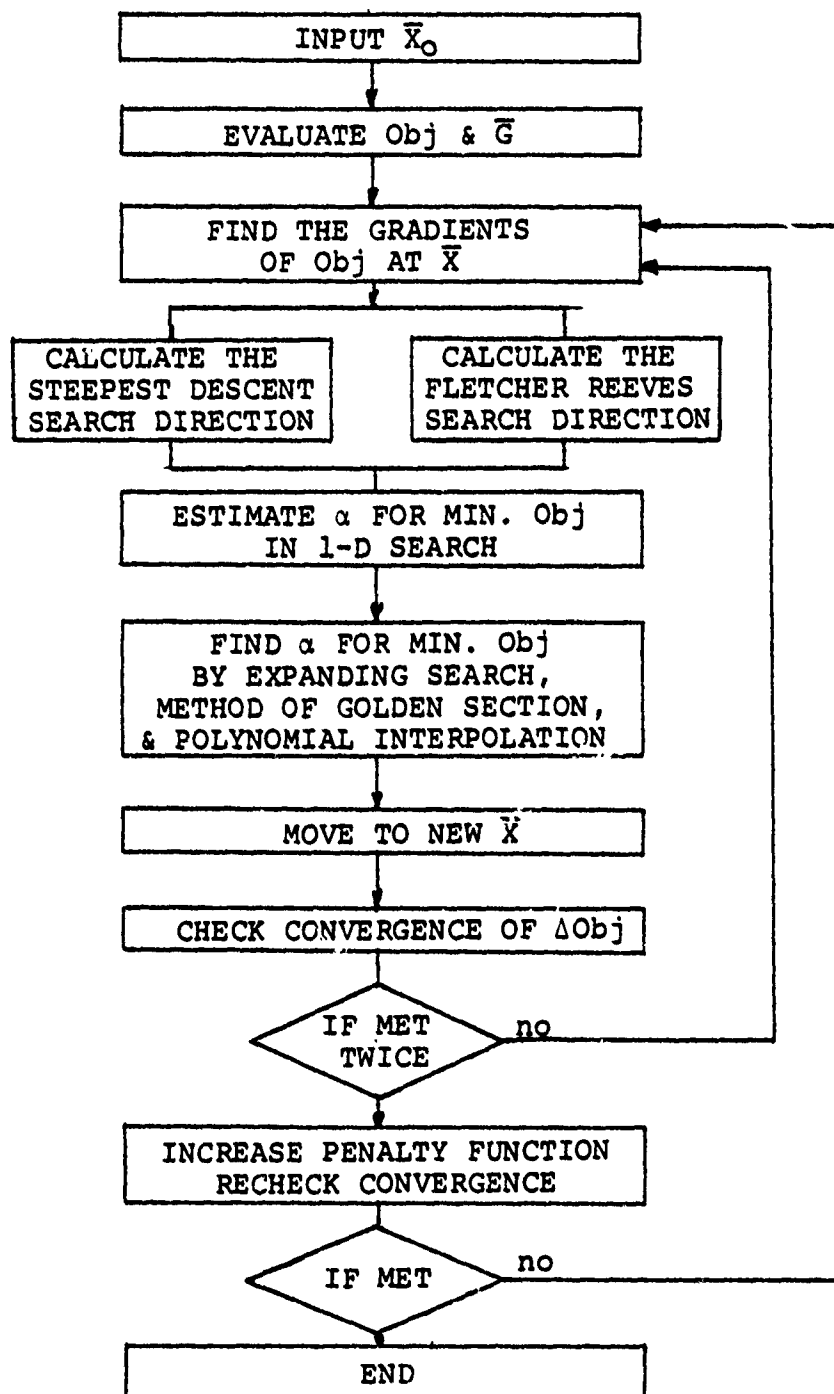


Figure 2. DESOP Flow Diagram

Proceeding with the optimization, there are two major loops in the optimization program. The outer loop increases the penalty function when the inner loop's convergence criteria have been met. A convergence test is then performed by the outer loop. If the convergence criteria is met, the optimization process is considered finished. If the convergence criteria for the outer loop is not met, program execution is returned to the inner loop. The inner loop performs successive iterations searching for the minimum of the penalized objective function with no increase in the penalty function taking place. When the inner loop's convergence criteria have been met program execution is transferred to the outer loop.

Execution of the program while in the inner loop proceeds as follows: First, the gradient of the penalized objective function is calculated by subroutine GRAD. The program then computes a search direction using either a steepest descent method or the method of conjugate directions developed by Fletcher and Reeves [Ref. 1]. Once a search direction is established the optimizer attempts to locate the minimum value of the penalized objective function in the search direction. This process is referred to as the one-dimensional search and is illustrated in Figure 3. The efficiency and accuracy to which the one-dimensional search for the minimum of the penalized objective function

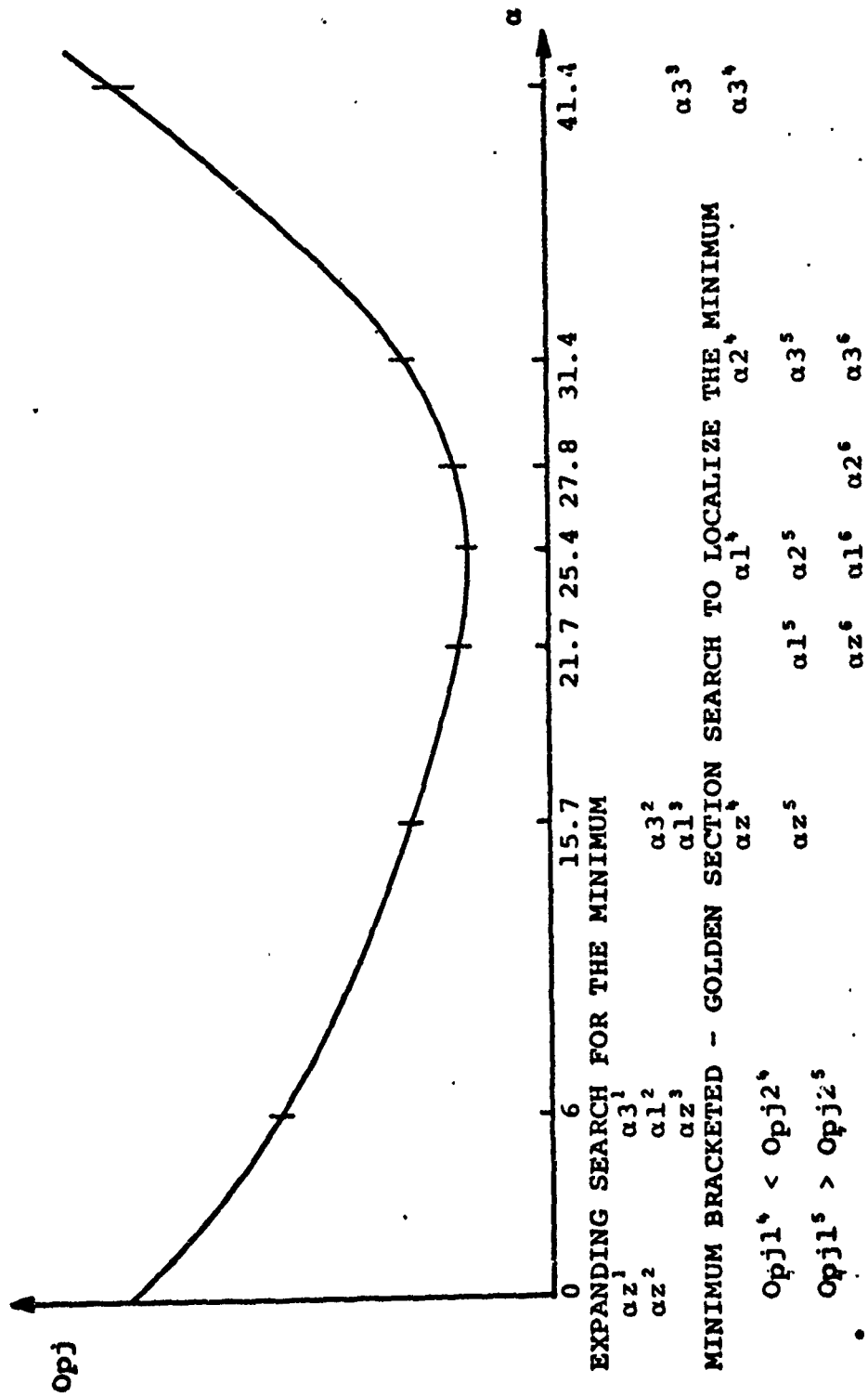


Figure 3. The One-Dimensional Search Process

is accomplished, is the key to successful sequential unconstrained minimization technique numerical optimization. The one-dimensional problem may be expressed in terms of the penalized objective function, Opj , and the amount of movement, α , in the search direction, \bar{S} . First the slope of Opj with respect to α is calculated. An initial "guess" of how far to move is made using subroutine ALPGES. The α which corresponds to the minimum value of Opj in the one-dimensional search is then calculated using subroutine ALPBND and subroutine QUEBIC. The minimum value of Opj thus found is then compared to the previous value of Opj for convergence using subroutine CONVRG. If convergence is not met, execution returns to the start of the inner loop. If convergence is met, execution returns to the outer loop.

When the convergence criteria have been met for both the inner and outer loops, the program proceeds to set $Icalc$ to three as a flag for user generated output for the final design. DESOP then provides the user with a hard copy output of the final design variables, objective function value, penalized objective value, constraint values, the number of inner loop iterations, the number of times the analysis subprogram was called and the final value of the penalty function. The OPCON program is then overlayed over the DESOP program and program execution is returned to the OPCON program.

2. Finding the Search Direction

The first step in finding the search direction, \bar{S} , is to determine the slope of Op_j at the present design point. The forward finite difference method is used where:

$$\frac{\partial F}{\partial X_i} = \frac{F(X_i + \Delta X_i) - F(X_i)}{\Delta X_i} = -S_i$$

$i = 1, 2, \dots, Ndv$

As $\partial F / \partial X_i$ gives the direction of positive slope, the search direction is the negative of $\partial F / \partial X_i$. The first search is performed using the steepest descent as found above using the following relation:

$$X'_i = X_i + \alpha S_i$$

where alpha is the distance moved in the \bar{S} direction. When a minimum is obtained along the direction of steepest descent, a new Fletcher-Reeves conjugate search direction [Ref. 1] is calculated at the new Design point using the following relations:

$$S'_i = \frac{\partial F}{\partial X_i} + BS_i$$

$$B = \frac{\sum_{i=1}^{Ndv} \left[\frac{\partial F'}{\partial X_i} \right]^2}{\sum_{i=1}^{Ndv} \left[\frac{\partial F}{\partial X_i} \right]^2}$$

where the prime denotes values for the present iteration and the non-prime variables indicate values for the previous

iteration. A one-dimensional search is then performed in the new search direction. Searches are continued using the conjugate direction method for $N_{dv} + 1$ iterations, where N_{dv} is the number of design variables. The search process is then restarted using the steepest descent method. The reason for incorporating the conjugate search method is that the steepest descent method when traversing a design surface with a curved valley will tend to zigzag from one side of the design surface valley to the other making very little progress as is illustrated in Figure 4. The conjugate direction method is much more efficient in traversing such a design surface. However, as the conjugate direction method is additive upon previous searches, it has a tendency to decrease in effectiveness with each successive search owing to the accumulation of numerical "noise." For that reason the search process is restarted with the steepest descent method every $N_{dv} + 1$ iterations, or when the conjugate direction predicts a positive slope. The search direction is normalized to avoid inaccuracies caused by numerical ill-conditioning.

3. Estimating an Initial Value for Alpha

The initial estimate for alpha is made in the following manner: First, the slope of Op_j in the search direction is calculated as the sum of each of the products of the gradients times the search direction. Then the slope of Op_j in the search direction is divided by the value

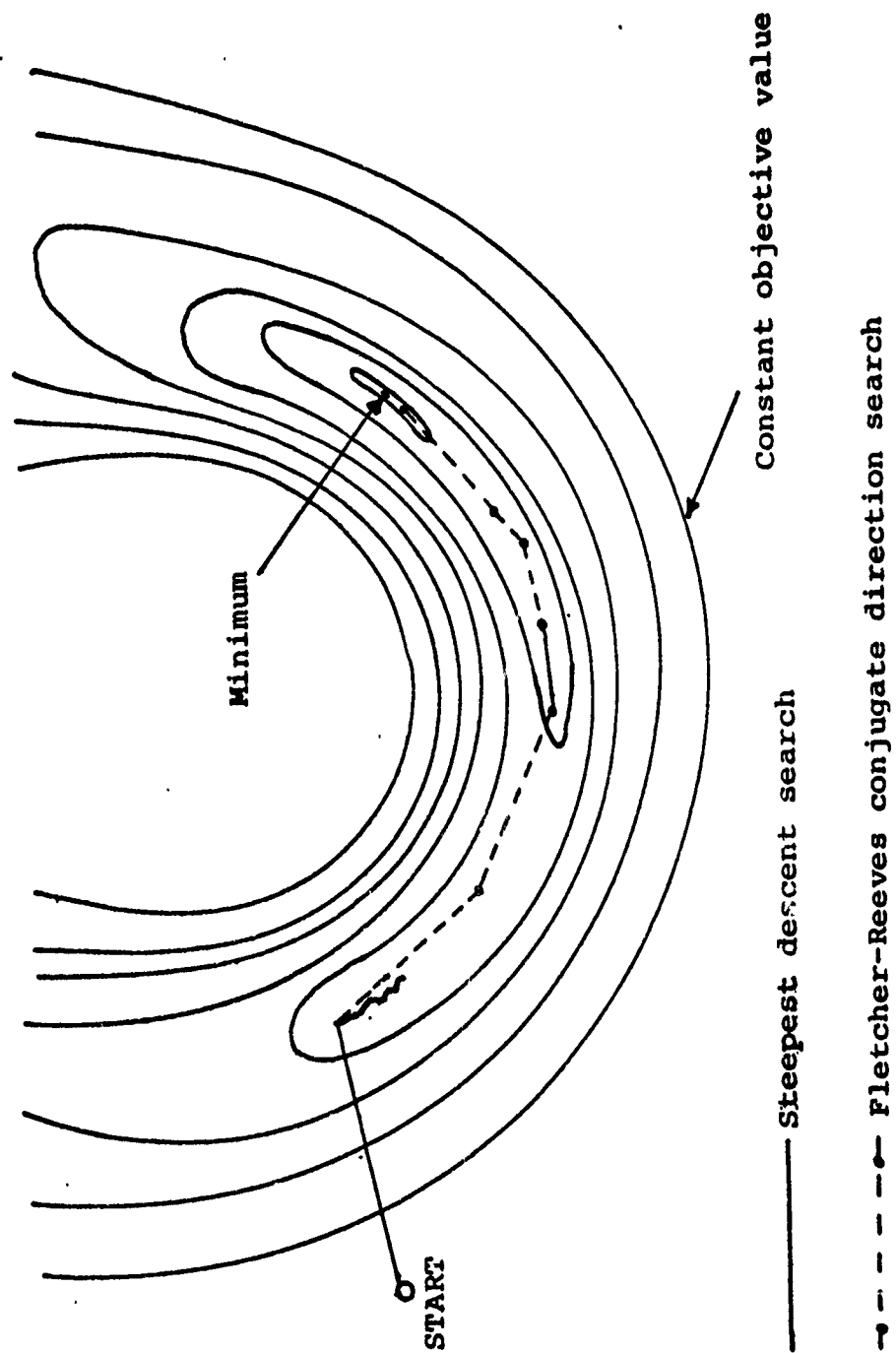


Figure 4. Steepest Descent and Conjugate Direction Search in a Two-Dimension Design Space.

of Opj . This value is then multiplied by an improvement percentage in Opj . This first estimate is then applied to a series of conditional tests to determine the validity of the estimate with respect to the slope of Opj and the magnitude of the design variables. Lastly, the estimate for α is checked to see if it violates any side constraints. If it does, the value of the estimate for α is reduced until the side constraints are no longer violated.

4. Calculating Alpha

The calculation of α is the most critical algorithm in the DESOP program in providing reliable optimizer operation. The ability to accurately and efficiently find the minimum of the penalized objective function in the one-dimensional search affects directly the operation of the optimizer. Figure 5 illustrates the zigzag phenomenon which occurs if α is not accurately found. The zigzag phenomenon is caused by the fact that the optimizer in performing the forward finite difference for calculating the search direction perturbs the design vector a very small amount. As such the optimizer can only "see" the design surface that is immediately adjacent to the design point. Therefore, if the minimum is not found in the one-dimensional search, the optimizer will converge very slowly on the minimum.

There are two major sections to the ALPBND subroutine. The first section attempts to find the minimum value of Opj

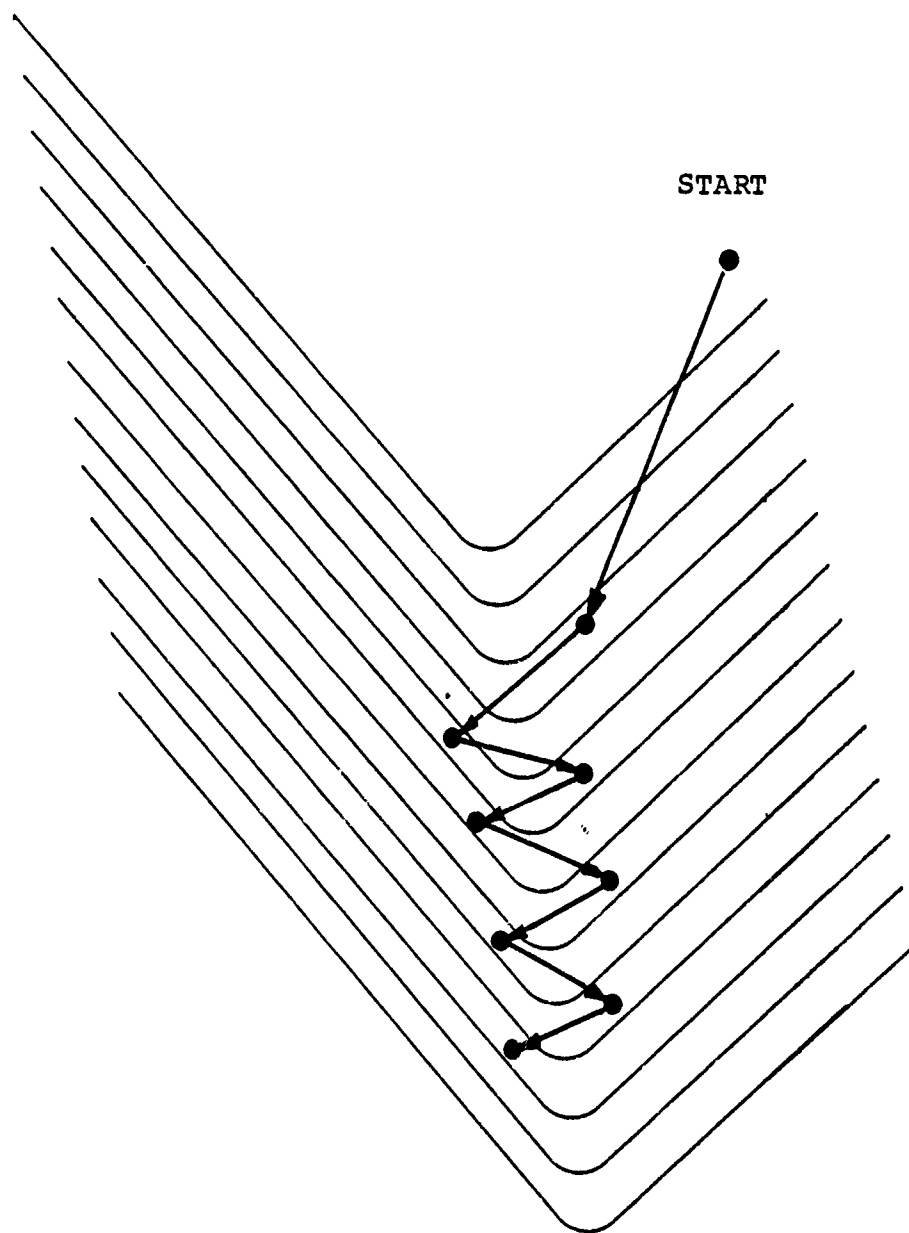


Figure 5. The Zigzag Phenomenon

using an expanding search technique. The first move is the amount predicted by the ALPGES subroutine. If the minimum is not bracketed by the first move, additional moves are made. Each move is larger than the last. The size of the move is increased each time by an amount equal to the size of the last move divided by the lower Golden Section fraction, where the Golden Section fractions are:

$$F_1 = \frac{3 - \sqrt{5}}{2}$$

$$F_2 = \frac{\sqrt{5} - 1}{2}$$

The lower Golden Section fraction, F_1 , is used so that the interval will be consistent with the Golden Section search in the second section of the ALPBND subroutine. The expanding search is continued until the minimum value of the objective function has been bracketed.

Once the minimum is bracketed, a Golden Section search is performed to reduce the bracketing interval on the minimum by an amount such that when the two end points of the interval are taken with two points internal to the interval and a cubic is passed through the four points, the cubic will accurately predict the minimum of the penalized objective function. Himmelblau in [Ref. 2] states that the Golden Section search method of reducing the interval around the minimum of Op_j is the most effective of the reducing techniques studied. Golden Section search is based

on the splitting of a line into two segments known in ancient times as the "Golden Section." The ratio of the whole line to the larger segment is the same as the ratio of the larger segment to the smaller segment. The two Golden Section fractions are employed to split the interval bracketing the minimum as shown in Figure 3. Once the interval has been split, the two values of Op_j corresponding to the internal points are compared to find the larger of the two. The internal point with the larger value of Op_j will become the new end point for the interval, the remaining interior point will by the fact that it was determined by a Golden Section fraction, be equal to the point determined by the other Golden Section fraction. Thus, only one new point must be calculated to continue the Golden Section search. The search is continued in this manner until the vertical separation of the two end points with respect to the interior points is less than one percent. The four values of the penalized objective function corresponding to the four Golden Section search points are then sent to a cubic interpolator. The cubic interpolator will return a value for α to predict the minimum of the penalized objective function, and the minimum of the cubic function that the interpolator has created. The subroutine ALPBND will then test the predicted minimum with the minimum found at the predicted α . If there is less than a tenth of

one percent difference between the two values of the objective function, the point predicted by the cubic interpolator will be accepted as the minimum and program execution will return to the main program. If the predicted minimum is not sufficiently close to the minimum at the predicted alpha, another Golden Section search will be performed to reduce the interval and better localize the minimum. The four points from the reduced interval will then be sent to the cubic interpolation subroutine. This process will continue until either the test for the minimum is positive or the interval has been reduced to less than $1E-12$. Program execution will then return to the main program.

5. Subroutine QUEBIC

Subroutine QUEBIC is used to estimate the alpha at which Opj is a minimum based on four point cubic interpolation. If the function more closely resembles a quadratic than a cubic, a three point quadratic interpolation is performed using the three points which bracket the minimum. If the predicted minimum is outside the interval spanned by the two end points again a quadratic interpolation is performed. If the minimum still lies outside the two end points, the analysis returns to subroutine ALPBND, the interval bracketing the minimum is reduced, and program execution returns to QUEBIC.

6. Convergence of the Penalized Objective Function

The penalized objective function is tested for convergence at the end of each inner loop and again at the end of the outer loop in the main program. Convergence is tested by calling subroutine CONVRG. There are two criteria used for testing for convergence. The first tests the relative difference of the value of Opj from the present iteration with the value of Opj from the last iteration. The second method tests the absolute difference of the two values. The second method is employed for cases when the value of the penalized objective function approaches zero. When convergence has been met on two successive iterations, the penalty function is increased by an amount specified by the user in the executive OPCON program. The penalized objective function is again tested for convergence. If convergence is still met, the optimizer considers the present value of the penalized objective function to be a minimum, noting again that numerical optimization programs cannot differentiate between local and global minimums.

7. The Penalty Function

The purpose of the penalty function is to increase the value of the objective function when the design is in an infeasible region. The infeasible region is that region where one or more design constraints are violated. When a constraint is violated, the value of the particular constraint,

G_j , is positive. The objective function is then penalized as follows:

$$Opj = Obj + R \cdot G_j^E$$

where:

R - a multiplication constant

E - an exponent constant

This type of penalty function, one where the penalty is applied after the design leaves the feasible region, is known as an exterior penalty function. The exterior type of penalty function was chosen over other types, such as the interior or extended interior penalty function. If a function is discontinuous within the design space being studied, numerical difficulties may be encountered which make performing an optimization of the design difficult.

III. SOLAR COLLECTOR OPTIMIZATION

A. THE CONCEPT OF NONIMAGING SOLAR COLLECTORS

At the present time there are numerous schemes for the collection of solar energy and its conversion to a more useful form of energy. In the field of solar collectors there are three broad categories: flat plate collectors, focusing collectors and nonimaging collectors. The advantages and disadvantages of each type are shown in Table I. Welford and Winston in [Ref. 3] report that "in the mid-1960's, it was realized in at least three different laboratories that light could be collected and concentrated for many purposes, including solar energy, more efficiently by nonimaging optical systems than by conventional image forming systems. The methodology of designing optimized nonimaging systems differs radically from conventional optical design. The new collectors approach very closely the maximum theoretical concentration; and for two-dimensional geometry, which is important for solar energy collection, this limit is actually reached."¹ Figure 6 shows the basic geometry for the nonimaging compound parabolic concentrating

¹Welford, W. T. and Winston, R., The Optics of Nonimaging Concentrators, Light and Solar Energy, p. ix, Academic Press, 1978.

TABLE I
Collector Type Advantages and Disadvantages

COLLECTOR TYPE	ADVANTAGES	DISADVANTAGES
FLAT PLATE	<p>Low initial cost Easy to manufacture Utilizes both direct and diffuse radiation No guidance required Good durability Low maintenance</p>	<p>Max. temperature 80°C Large start up losses Large convective and thermal radiation losses</p>
FOCUSING	<p>Max. temperature 200+3000C Low startup losses Low convective and thermal radiation losses</p>	<p>High manufacturing cost due to requirement for highly specular reflecting surfaces Require accurate tracking Maintenance high as reflective surface remains uncovered Does not accept diffuse radiation</p>
NONIMAGING	<p>Accepts both diffuse and direct radiation No tracking required Reflective surface covered</p>	<p>Moderate convective and radiation losses Moderate manufacturing costs per- formance improved by slight im- perfections in specular reflection Moderate operating temperatures 80+300C</p>

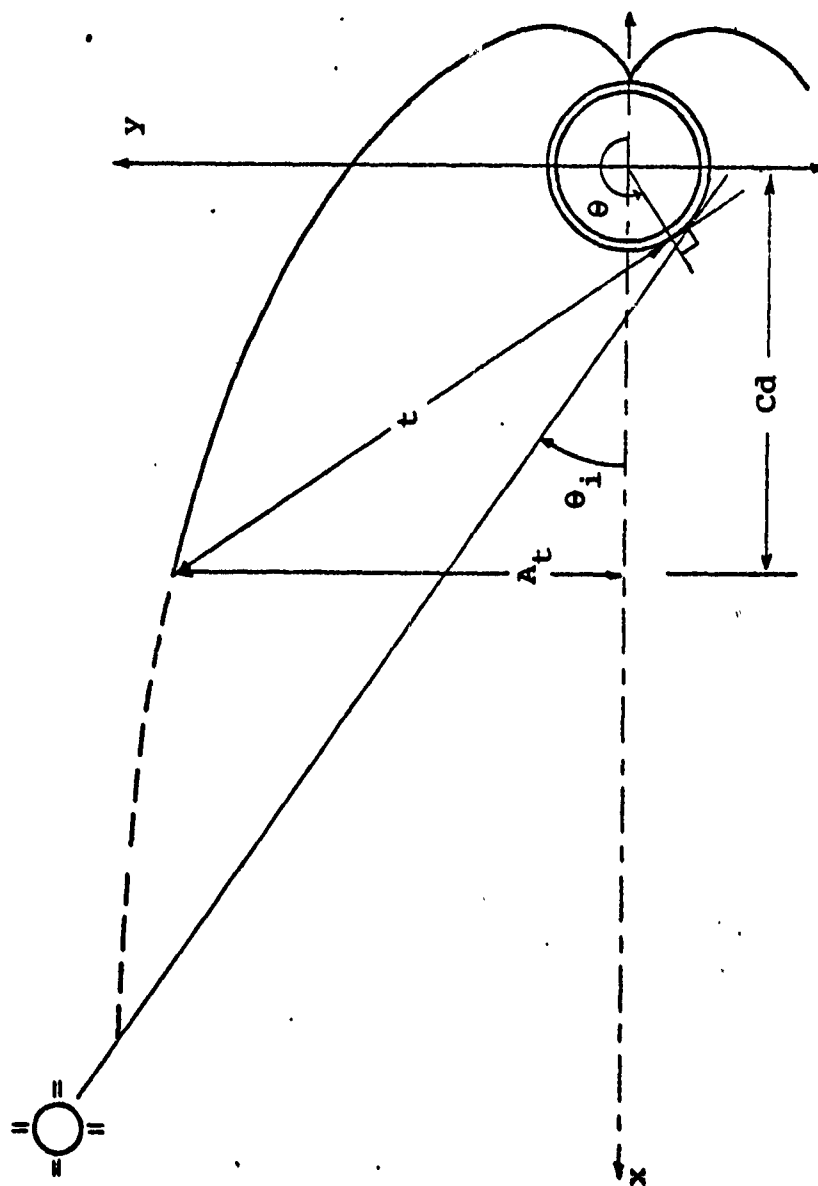


Figure 6. Nonimaging Concentrating Solar Collector Geometry

collector. Welford and Winston [Ref. 3] have shown that the concentration for a maximum input acceptance half-angle, θ_i , is obtained in two sections. The first section, that shadowed from the direct rays at angles less than θ_i is an involute of the receiver cross section. The second section is such that rays at θ_i are tangent to the receiver after one reflection at the reflector surface. The x-y coordinates of a point on the reflector surface for a collector with a circular receiver may be expressed as:

$$x = -r \cdot \cos\theta + t \cdot \cos(\theta + \pi/2)$$

$$y = r \cdot \sin\theta - t \cdot \sin(\theta + \pi/2)$$

$$\text{where for } \pi/2 + \theta_i \leq \theta \leq 3\pi/2 - \theta_i$$

$$t = \frac{r((\theta + \theta_i \pi/2) - \cos(\theta - \theta_i))}{1 + \sin(\theta - \theta_i)}$$

$$\text{and for } \theta \leq \theta_i + \pi/2$$

$$t = r \cdot \theta$$

r - receiver radius

θ - an angle measured from the collector centerline as shown in Figure 6.

The concentration ratio, CR, of the collector is defined as the aperture area of the collector, $2A_t$, divided by the surface area of the receiver. For the collector shown

$$CR = \frac{2A_t}{2\pi r}.$$

The collector depth, C_d , is used in the economic analysis of collector cost. The truncation angle, θ_t , is the maximum θ used in determining the collector geometry for the truncated collector. The collector may be significantly truncated before any appreciable change in the concentration ratio is affected. This allows a savings in manufacturing costs with little degradation in collector performance.

The nonimaging concentrating solar collector will accept and deliver to the absorber all incident radiation that falls on the collector aperture and that is within the maximum acceptance half angles, θ_i . That is, there is an arc of sky, $2\theta_i$, from which all radiation, direct, diffuse and reflected, is delivered to the absorber. It is this fact which makes the nonimaging concentrating collector attractive for solar energy use. Figures 7, 8, and 9 show ray paths for a nonimaging, truncated collector for the following cases: In Figure 7 the solar altitude is within the acceptance half angles. In Figure 8 the solar altitude is equal to the acceptance half angle. In Figure 9 the solar angle is less than the acceptance half angle. In Figure 7, all the radiation that enters the collector is delivered to the absorber tube and is somewhat scattered over the absorber surface. In Figure 8 again all the radiation that enters the collector is delivered to the absorber tube, but is now tangent to the tube and is concentrated on the front edge of the absorber tube. In

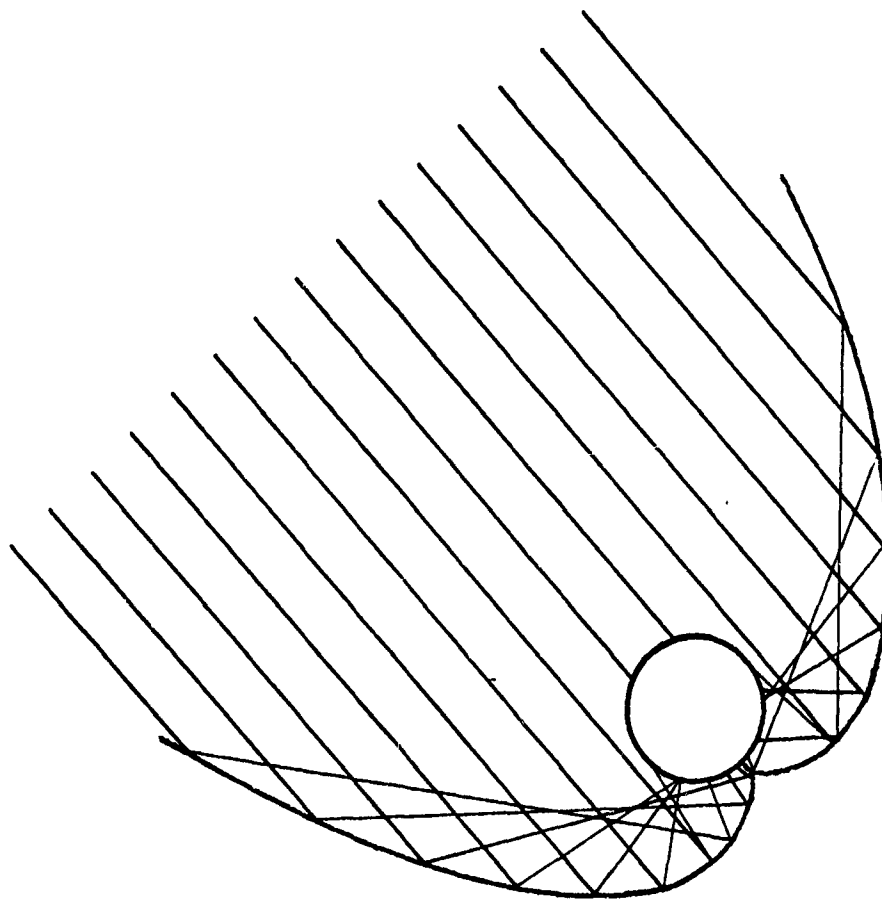


Figure 7. Ray Path Drawing for Solar Altitude Within the Maximum Acceptance Half Angle

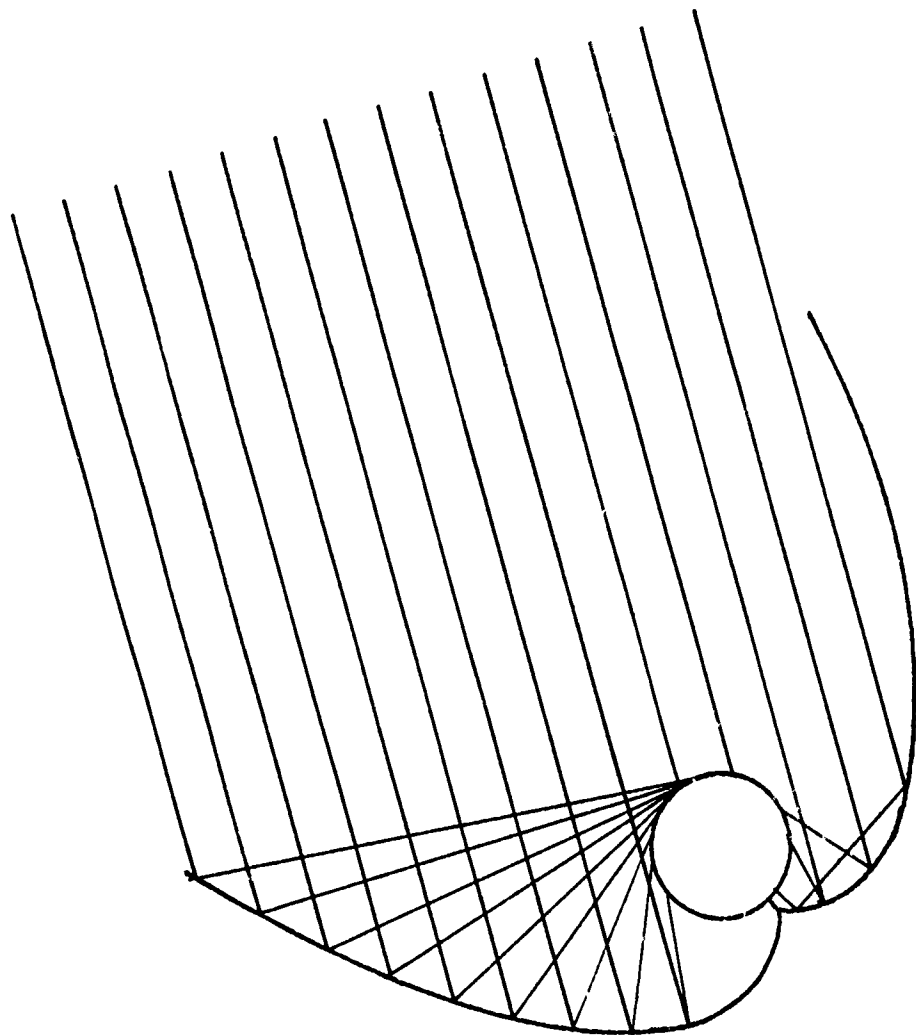


Figure 8. Ray Path Drawing for Solar Altitude Equal to the Maximum Acceptance Half Angle

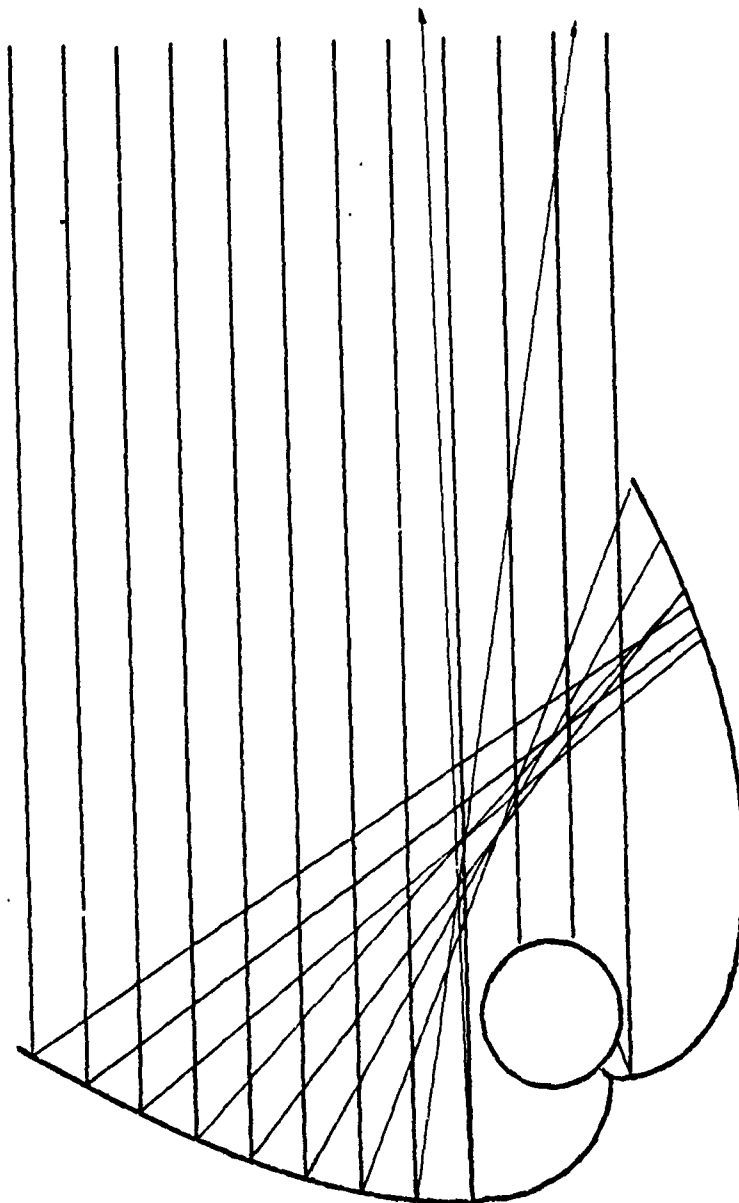


Figure 9. Ray Path Drawing for Solar Altitude Outside the Maximum Acceptance Half Angle

Figure 9 all the reflected radiation leaves the collector, thus the acceptance half angle provides a very sharp cutoff angle for accepting incident radiation.

B. SOLAR COLLECTOR DESIGN PROGRAM

A NonImaging compound parabolic trough Solar Collector hereafter referred to as NISCO was chosen to model in the analysis program. There are seven major heat flow paths considered in the program. The major heat flow paths are shown in Figure 10 and are outlined below:

q_1 - The sum of the direct, diffuse and ground reflected radiation that is incident on the collector cover.

q_2 - The sum of the direct, diffuse and ground reflected radiation that is reflected by the collector cover.

q_3 - The sum of the direct, diffuse and ground reflected radiation that is absorbed by the collector cover.

q_4 - The sum of the direct, diffuse, and ground reflected radiation that is transmitted by the cover and delivered either directly or indirectly to the absorber and is absorbed by the absorber.

q_5 - The sum of the radiation reflected by the absorber that is absorbed by the cover and the thermal radiative and convective exchanges between the absorber and the cover.

q_6 - The sum of the thermal radiative and the convective exchanges between the cover and the environment.

q_7 - The energy delivered to the collector coolant.

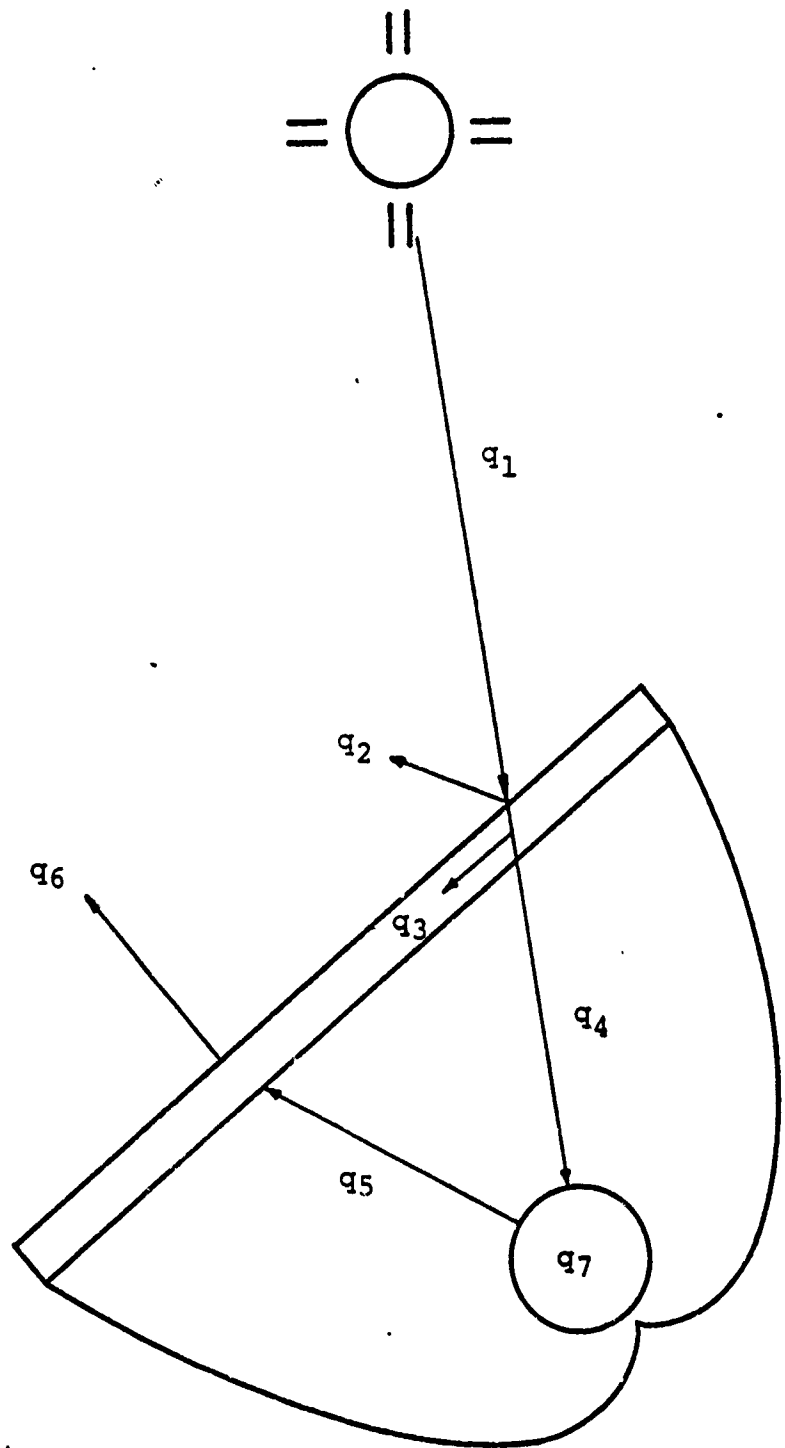


Figure 10. Basic Solar Collector Heat Paths

To determine the energy balance on the collector, a procedure outlined by Kreith and Kreider, [Ref. 6] is followed. All important heat fluxes are first calculated from basic heat-transfer principles. The fluxes are then combined in heat-balance equations for the receiver, the aperture cover, and the coolant fluid. Since the various flux terms are nonlinear in temperature a simultaneous iterative solution is used to solve the equations. Note that the first page of Appendix G is a cross reference list of the major equations used in the subprogram NISCO and the sources used to obtain the equations.

The following discussion will detail the procedure used in the NISCO subprogram to calculate the heat gain for a particular solar collector design and the resultant life-cycle fuel savings. Variable names and program line numbers correspond to those used in the NISCO subprogram. The design variables chosen for the NISCO subprogram were: (1) θ_{ai} , (θ_i), the maximum acceptance half angle, (2) θ_{at} , (θ_t), the truncation angle, (3) R , (r), the receiver radius, (4) L , the collector length, and (5) M_{fr} , (\dot{m}), the coolant mass flow rate. The objective function of the NISCO subprogram is the life-cycle fuel savings of the collector. Life-cycle fuel savings are calculated as the cost savings realized by the collector over purchasing natural gas per unit quantity of 10^6 Btu's expressed in present worth using the present worth analysis described by Newnan in [Ref. 13]. The constraints

placed upon the design by the NISCO subprogram were: the maximum and minimum values allowed for the truncation angle due to collector geometry as specified in Section III.A., the mass flow rate of the coolant must be positive, the receiver radius must be positive, a minimum average daily heat gain, and a maximum allowable coolant temperature. The side constraints placed upon the design to ensure that the final design was a reasonable design were: the maximum acceptance half angle must be greater than three degrees but less than 85 degrees, the truncation angle must be greater than 185 degrees but less than 260 degrees, the receiver radius must be greater than one tenth inch but less than two inches, the collector length must be greater than five feet but less than 100 feet, and the mass coolant flow rate must be greater than five lbm/hr and less than 1000 lbm/hr.

The NISCO analysis subprogram proceeds as follows. A minimum average daily heat gain is specified and entered as Q1 in line 1655. The subprogram is then SAVED and the OPCON/DESOP optimization program run. When DESOP calls the NISCO subprogram, it will pass the design variable vector \bar{X} to the NISCO subprogram. The NISCO subprogram in lines 205 to 225 sets the design variable vector \bar{X} equal to the design variables used in the NISCO subprogram. NISCO then proceeds to read in the constants and data used in the solar collector design. The design specifications

are summarized in Appendix B. Collector geometry calculations are then performed in lines 820 to 855 to ascertain the optical properties of the collector as developed in [Ref. 3]. An initial receiver and aperture cover temperature is assumed in lines 865 and 870. Monthly calculations are then performed to calculate the collector tilt angle, the minimum accepted solar altitude, the ground angle factor and sky heat loss constants as specified in [Refs. 5 and 6]. An hourly calculation is then performed to calculate the angle that the sun makes with the collector aperture cover, the amount of radiation incident on the collector aperture cover and the collector cover transmissivity and absorptance as specified in [Refs. 5 and 6]. The iterative portion of the analysis then proceeds as follows: First, the heat transfer coefficients for the collector are calculated as prescribed in [Refs. 4, 6 and 11], lines 1060 to 1145. Next a heat balance is performed on the cover as prescribed in [Ref. 6] and a new collector aperture cover, T_{ap} , is calculated in lines 1155 to 1210. A heat balance is then performed on the receiver as specified in [Ref. 6] and the energy passed to the coolant, Q_u , is calculated in lines 1225 to 1305. Finally a heat balance is performed on the coolant as prescribed in [Ref. 6] and the coolant exit temperature is calculated in lines 1320 to 1365. Knowing the coolant exit temperature, T_{c2} , an average receiver

temperature may be calculated and compared to the initial assumed receiver temperature, lines 1375 to 1405. If the new receiver temperature is within a tenth of one percent of the old receiver temperature, the analysis program proceeds to calculate the pumping power required for the collector. If the new receiver temperature is not within the convergence specified, the iterative heat balance process is repeated, setting the aperture cover temperature and the receiver temperature to the new value calculated. The pressure drop through the collector and the power required to pump the coolant through the collector are calculated in lines 1430 to 1480, as specified in [Refs. 6 and 12]. The energy required to pump the coolant through the collector is then subtracted from the energy gained by the collector to calculate the available collector energy, Q_a , line 1490. Q_a is then summed for each hour that the analysis is performed. As the analysis is performed for one day each month, the summation of the available collector energy is then multiplied by thirty to obtain a yearly heat gain, Q_y , line 1590. The cost of an equivalent amount of natural gas is then calculated. Using present worth analysis as described in [Ref. 13], a life-cycle savings is then calculated and the initial manufacturing cost of the collector is calculated and subtracted from the life-cycle savings. This result is then divided by the life-cycle

useful energy gain by the collector and multiplied by 10^6 to obtain the life-cycle fuel savings used as the objective function for the optimization program. The constraints on the design are then calculated in lines 1660 to 1685. Lines 1710 to 1815 contain printout specifications for the first and the last time that the NISCO subprogram is called by the optimization program. The values of the objective function and the constraints are then passed along with program control back to the optimization program.

IV. RESULTS

A major portion of the thesis work was devoted to the development of a reliable optimization program that would optimize a wide variety of problems. Following the accomplishment of this goal, a subprogram was developed to model a nonimaging concentrating compound parabolic trough solar collector.

A. RESULTS OF THE DESOP PROGRAM DEVELOPMENT

In developing the DESOP numerical optimization program, four standard numerical optimization test problems were used. The four test problems provided a wide variety of different numerical problems with which the optimization program had to deal. The four test problems are listed in Appendix F. A major goal of this thesis was to optimize all four problems using default optimizer control variables. The results of the DESOP program optimizing the four test problems are given in Appendix A. The DESOP program was able to make significant design improvements in all four test problems using default optimizer control parameters. When the optimizer control parameters were adjusted for each individual problem, the DESOP program's performance was improved in all four cases. Further experimenting with the optimizer control parameters could lead to an even better performance of the DESOP program.

B. RESULTS OF THE NISCO SUBPROGRAM

A listing of the NISCO subprogram is included as Appendix G. There are numerous comment statements in the subprogram. The reader is encouraged to look closely at the subprogram. The results of the NISCO subprogram may be found in Appendix B. The first section of Appendix B details the design specifications that were chosen for the solar collector model. Three different daily heat capacities were specified 10000, 30000 and 50000 Btu, and the NISCO subprogram was used to find the optimum design for each. The second section of Appendix B gives the initial design and final designs for the three solar collector capacities. In each case the DESOP program was able to significantly improve the design. The instantaneous efficiencies for the final designs are within a few percent of the instantaneous efficiency reported by Kreith and Kreider [Ref. 6] for a slightly different nonimaging concentrating compound parabolic trough solar collector operating under slightly different atmospheric conditions. It is interesting to note that the larger capacity solar collector had the best instantaneous efficiency and also the highest life-cycle fuel savings. In all three cases the optimum incident acceptance angle was found to be 18.04 - 18.05 degrees and the optimum truncation angle was found to lie within the range of 184.55 to 190.0 degrees.

Due to the fact that the objective function is weakly linked to the design capacity of the solar collector, the final daily heat gain is somewhat higher than the minimum set. If a stronger link were to be established between the solar collector capacity and the objective function, the collector design would be driven closer to the stated minimum daily average heat gain. Also, if the convergence criteria is tightened, the optimizer will take longer to reach the minimum but will reach a final design where the average daily heat gain is closer to the minimum set.

APPENDIX A

DESOP TEST PROGRAM RESULTS

This appendix contains the results of the four test programs that were used to develop the DESOP numerical optimization program. For each design the initial design, the true optimum design, the DESOP results using default control parameters, and the DESOP results using adjusted control parameters are given. The four test programs may be found in Appendix F.

DESOP TEST PROGRAM

ANALIZ Subprogram : BANNA

Initial Design:

Design Variables:

X(1) = -1.2

X(2) = 1.0

Objective Function:

Obj = 10.8

Opj = 10.8

Side Constraints Violated:

N/A

Constraints Violated:

N/A

True Optimum:

Design Variables:

X(1) = 1.00

X(2) = 1.00

Objective Function:

Obj = 4.00

Opj = 4.00

Side Constraints Violated:

N/A

Constraints Violated:

N/A

DESOP Results:

Default Control Parameters:

Design Variables:

X(1) = 0.768

X(2) = 0.578

Objective Function:

Obj = 4.05

Opj = 4.05

Side Constraints Violated:

N/A

Constraints Violated:

N/A

of Function Evaluations:

96

Adjusted Control Parameters

Design Variables:

X(1) = 0.791

X(2) = 0.606

Objective Function:

Obj = 4.047

Opj = 4.047

Side Constraints Violated:

N/A

Constraints Violated:

N/A

of Function Evaluations:

91

NOTE: The BANNA subprogram has 2 design variables and no constraints.

DESOP TEST PROGRAM

ANALIZ Subprogram : Rosen-Suzuki

Initial Design:

Design Variables:

X(1) = 1
X(2) = 1
X(3) = 1
X(4) = 1

Objective Function:

Obj = 31
Opj = 31

Side Constraints Violated:

N/A

Constraints Violated:

None

True Optimum:

Design Variables:

X(1) = 0.0
X(2) = 1.0
X(3) = 2.0
X(4) = -1.0

Objective Function:

Obj = 6.00
Opj = 6.00

Side Constraints Violated:

N/A

Constraints Violated

None

DESOP Results:

Default Control Parameters

Design Variables:

X(1) = 4.72E-02
X(2) = 0.998
X(3) = 1.98
X(4) = -1.00

Objective Function:

Obj = 6.088
Opj = 6.093

Side Constraints Violated:

N/A

Constraints Violated:

G(3) = 0.000527

of Function Evaluations:

392

Adjusted Control Parameters

Design Variables:

X(1) = -5.167E-03
X(2) = 1.019
X(3) = 1.999
X(4) = -0.9951

Objective Function:

Obj = 5.9998
Opj = 6.007

Side Constraints Violated:

N/A

Constraints Violated:

G(3) = 0.00232

of Function Evaluations:

306

NOTE: The Rosen-Suzuki subprogram has four design variables
and three constraints.

DESOP TEST PROGRAM

ANALIZ Subprogram : T5VAR

Initial Design:

Design Variables:

X(1) = 25.2
X(2) = 2.0
X(3) = 37.5
X(4) = 9.25
X(5) = 6.8

Objective Function:

Obj = 3.52E+08
Opj = 1.64E+14

Side Constraints Violated:

1

Constraints Violated:

3

True Optimum

Design Variables:

X(1) = 4.538
X(2) = 2.400
X(3) = 60.00
X(4) = 9.300
X(5) = 7.000

Objective Function:

Obj = -5.28E+06
Opj = -5.28E+06

Side Constraints Violated:

None

Constraints Violated:

None

DESOP Results:

Default Control Parameters:

Design Variables:

X(1) = 1.12
X(2) = -0.163
X(3) = 37.5
X(4) = 13.5
X(5) = 10.6

Objective Function:

Obj = -7.36E+06
Opj = -7.36E+06

Side Constraints Violated:

X(2)_l = 1.2
X(4)_u = 9.3
X(5)_u = 7.0

Constraints Violated:

None

of Function Evaluations:

161

Adjusted Control Parameters:

Design Variables:

X(1) = 1.72
X(2) = -1.56E-02
X(3) = 37.5
X(4) = 12.3
X(5) = 9.10

Objective Function:

Obj = -6.66E+06
Opj = -6.65E+06

Side Constraints Violated:

X(2)_l = 1.2
X(4)_u = 9.3
X(5)_u = 7.0

Constraints Violated:

G(6) = 138

of Function Evaluations:

69

NOTE: The T5VAR subprogram has five design variables and six constraints.

DESOP TEST PROGRAM

ANALIZ Subprogram : T7VAR

Initial Design:

Design Variables:

X(1) = 1
X(2) = 1
X(3) = 1
X(4) = 1
X(5) = 1
X(6) = 1
X() = 1

Side Constraints Violated:

None

Objective Function:

Obj = -203
Opj = 1007

Constraints Violated:

G(1) = 11

True Optimum:

Design Variables:

X(1) = 3
X(2) = 0
X(3) = 0
X(4) = 1
X(5) = 0
X(6) = 0
X(7) = 0

Side Constraints Violated:

None

Objective Function

Obj = -190
Opj = -190

Constraints Violated:

None

DESOP Results:

Default Control Parameters:

Design Variables

X(1) = 1.42
X(2) = 0.515
X(3) = 0.376
X(4) = 0.844
X(5) = 2.13E-02
X(6) = 9.84E-03
X(7) = 0.638

Side Constraints Violated:

None

Objective Function:

Obj = -142
Opj = -142

Constraints Violated:

None

of Function Evaluations:

302

Adjusted Control Parameters:

Design Variables:

X(1) = 2.69
X(2) = -7.60E-04
X(3) = 1.04E-02
X(4) = 1.82
X(5) = 2.89E-03
X(6) = 2.91E-03
X(7) = 0.113

Side Constraints Violated:

1

Objective Function:

Obj = -178.6
Opj = -179.1

Constraints Violated:

None

of Function Evaluations:

808

NOTE: The T7VAR subprogram has seven design variables and one constraint.

APPENDIX B

NISCO DESIGN RESULTS

DESIGN SPECIFICATIONS

A. GEOGRAPHIC

Location	40 degrees North Latitude
Solar position and intensity levels	ASHRAE Handbook of Fundamentals standard solar radiation design, Ref.
Wall azimuth angle	0 deg.
Cloud Cover	0 %
Vapor Pressure	3 mm Hg
Tamb	ASHRAE Handbook of Fundamentals daily norms for San Francisco, Ca. Ref.

B. COLLECTOR MATERIALS

RECEIVER	Oxidized Copper
Absoptivity	0.93
Thermal Emissivity	0.40
Reflectivity	0.07
REFLECTOR	Vacuum deposited Aluminum on resin
Reflectivity	0.89
COVER	Double strength window glass
Specular Absorptance	ASHRAE standards for D.S. window
Specular Transmisivity	glass. Ref.
Absorptance av.	0.03
Transmittance av.	0.80
Reflectivity av.	0.17
Thermal Emissivity	0.94
COOLANT	Therminol 55
Specific gravity	0.87
Specific heat†	$4.9E-4 \cdot Tr + 0.4036$ Btu/(lbm F)
Viscosity†	$6.71955E-4 \cdot (-0.053 \cdot Tr + 32.3)$ lbm/(ft sec)
Inlet Temperature	100 deg. F

† Values given as a function of average receiver temperature, Tr, in degrees F.

C. ECONOMIC

Life-Cycle	20 years	
Fuel Cost (Natural Gas)	8.14	$\$/10^6$ Btu
Annual Fuel Inflation Rate	0.11	
Monetary Inflation Rate	0.10	
Collector Cost	22.5	$\$/ft^3$ Ref. 4

NISCO DESIGN - 10000 Btu/DAY SOLAR COLLECTOR

INITIAL DESIGN

Design Variables:

Incident acceptance half angle	25.00 deg
Truncation angle	230.0 deg
Receiver radius	0.41 in
Collector length	20.00 ft
Coolant mass flow rate	108.7 lbm/hr

Design Features:

Concentration ratio	2.20
Collector aperture area	9.56 ft ²
Collector depth	4.12 in
Coolant velocity	0.15 ft/sec
Average daily heat gain	11,400 Btu
Maximum coolant temperature	137 deg F
Instantaneous collector efficiency	0.70
Initial cost	\$203.00
Life-cycle cost savings	\$7.78 /10 ⁶ Btu

FINAL DESIGN

Design Variables:

Incident acceptance half angle	18.05 deg
Truncation angle	190.0 deg
Receiver radius	0.52 in
Collector length	18.92 ft
Coolant mass flow rate	124.3 lbm/hr

Design Features:

Concentration ratio	1.65
Collector aperture area	8.48 ft ²
Collector depth	1.02 in
Coolant velocity	0.11 ft/sec
Average daily heat gain	10,600 Btu
Maximum coolant temperature	131 deg F
Instantaneous collector efficiency	0.74
Initial cost	\$159.00
Life-cycle cost savings	\$8.15 /10 ⁶ Btu

NISCO DESIGN - 30000 Btu/DAY SOLAR COLLECTOR

INITIAL DESIGN:

Design variables:

Incident acceptance half angle	15.00 deg.
Truncation angle	230.0 deg.
Receiver radius	1.00 in.
Collector length	50.0 ft.
Coolant mass flow rate	100.0 lbm/hr

Design features:

Concentration ratio	2.95
Collector aperture area	77.35 ft ²
Collector depth	12.62 in.
Max. coolant temperature	366.59 F
Instantaneous collector efficiency	0.64
Average daily heat gain	83,400 Btu
Initial cost	\$1,628.90
Life cycle savings	\$7.54 / 10 ⁶ Btu

FINAL DESIGN:

Design variables:

Incident acceptance half angle	18.04 deg.
Truncation angle	184.55 deg.
Receiver radius	1.28 in.
Collector length	26.43 ft.
Coolant mass flow rate	425.23 lbm/hr

Design features:

Concentration ratio	1.54
Collector aperture area	27.35 ft ²
Collector depth	1.78 in.
Coolant velocity	6.04E-02 ft/sec
Max. coolant temperature	129.4 F
Instantaneous collector efficiency	0.75
Average daily heat gain	34,473 Btu
Initial cost	\$509.98
Life-cycle savings	\$8.19 / 10 ⁶ Btu

Run time - approx. 5 hours

NISCO DESIGN - 50000 Btu/DAY SOLAR COLLECTOR

INITIAL DESIGN

Design Variables:

Incident acceptance half angle	20.00 deg.
Truncation angle	220.0 deg.
Receiver radius	1.25 in.
Collector length	50.00 ft.
Coolant Mass flow rate	500.0 lbm/hr

Design Features:

Concentration ratio	7.28
Collector aperture area	75.5 ft ²
Collector depth	9.14 in.
Coolant velocity	7.51E-02 ft/sec
Maximum coolant temperature	164. deg. F
Instantaneous efficiency	0.72
Average daily heat gain	91,900 Btu
Initial cost	\$1,510.00
Life-cycle savings	\$7.96 / 10 ⁶ Btu

FINAL DESIGN

Design Variables:

Incident acceptance half angle	18.04 deg.
Truncation angle	185.0 deg
Receiver radius	1.43 in
Collector length	39.3 ft
Coolant mass flow rate	986 lbm/hr

Design Features:

Concentration ratio	1.55
Collector aperture area	45.5 ft ²
Collector depth	2.04 in
Coolant velocity	0.11 ft/sec
Maximum coolant temperature	121 deg F
Instantaneous collector efficiency	0.76
Average daily heat gain	57,800 Btu
Initial cost	\$848.00
Life-cycle savings	\$8.21 / 10 ⁶ Btu

APPENDIX C
DESOP USER'S MANUAL

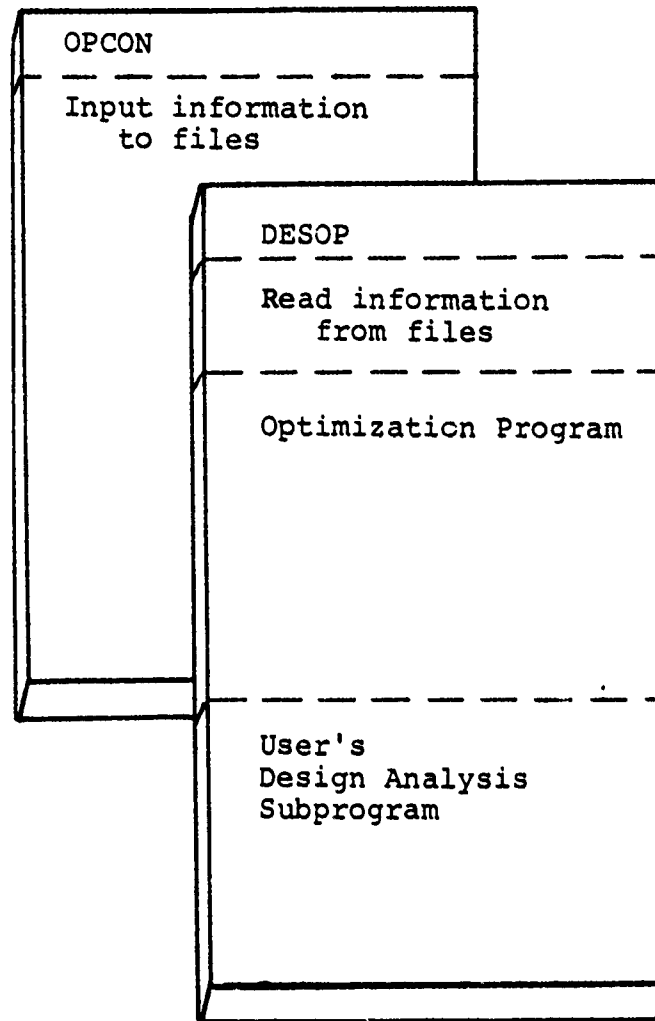
A. INTRODUCTION

The numerical optimization package of programs, currently consisting of OPCON and DESOP, provide the capability for finding the optimum design of a system mathematically modeled using multiple variables, on the Hewlett-Packard 9845A desktop computer. OPCON is an executive program which provides the user with the following: a primary point of contact with the computer from which to access the optimization program DESOP, a standard formatted input for design variables, side constraints on the design variables, optimizer control variables, and organization of the optimization process. DESOP is a numerical optimization program, which when coupled to a user supplied design analysis program, will optimize the design. DESOP will allow the user to monitor the optimization process as it is taking place. After monitoring the optimization process, the user may choose to change the optimizer control variables and/or his design starting point to more efficiently or more accurately reach the design optimum. After an optimization has been performed, DESOP will reload the OPCON program and return the user to the OPCON program. The OPCON program will then offer the

user the following three choices: to optimize the same design, optimize a different design or terminate the program.

Figure 11 illustrates the overlay method used in loading the OPCON and DESOP programs.

PROGRAM OVERLAY STRUCTURE



MASS STORAGE

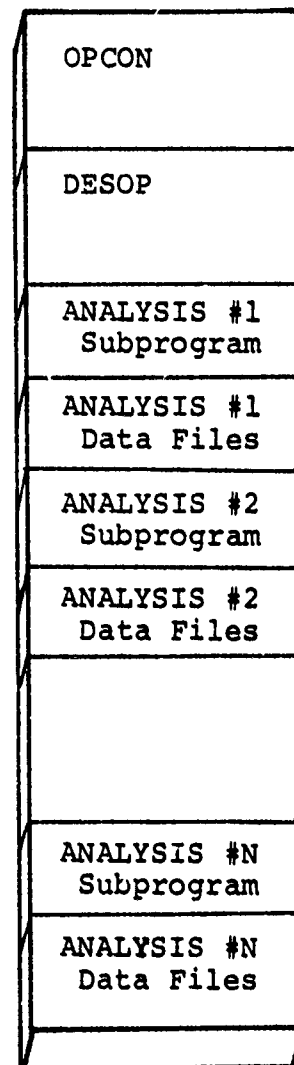


Figure 11. Basic Program Relationships

B. THE CONCEPT OF NUMERICAL OPTIMIZATION

Consider the problem of designing the cantilevered beam shown in Figure 1. The design task may be broken down into three major parts. First, the objective of the design must be determined, which in this case is to minimize the weight of the beam required to support the concentrated tip load P . Second, any physical constraints that may effect the design must be determined. Thirdly, any limits which exist on the design variables must be determined. The design problem may then be reduced to a system of equations as follows:

Minimize the volume (V)

$$V = B \cdot H \cdot L$$

Subject to:

Bending stress (σ_b)

$$\sigma_b = \frac{6 \cdot P \cdot L}{B \cdot H^2} \leq 20000 \text{ psi}$$

Shear stress (v)

$$v = \frac{3 \cdot P}{2 \cdot B \cdot H} \leq 10000 \text{ psi}$$

Deflection under load (δ)

$$\delta = \frac{4 \cdot P \cdot L^3}{E \cdot B \cdot H^3} - 1 \text{ inch}$$

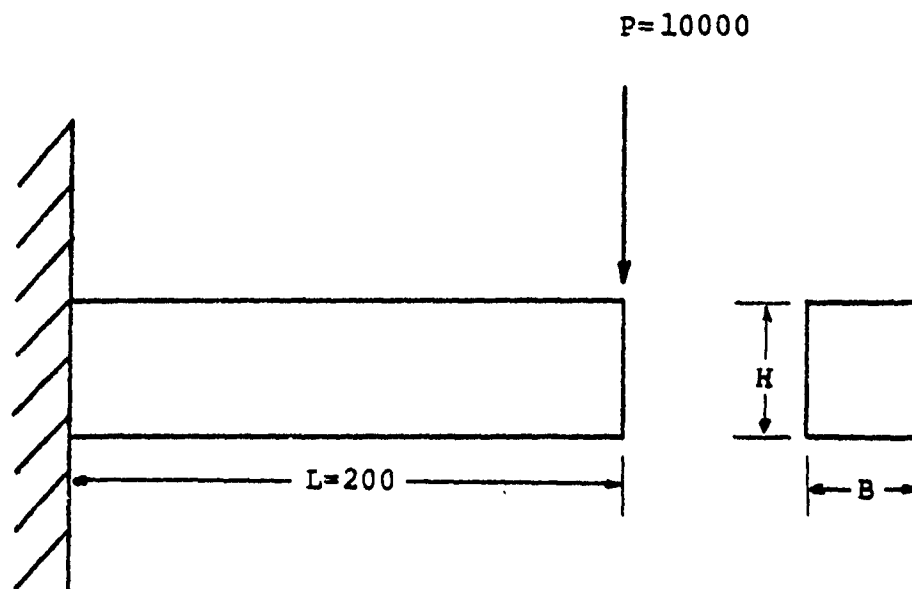


Figure 1. Cantilevered Beam Design Problem

With geometric constraints such that:

$$0.5 \leq B \leq 0.5$$

$$1.0 \leq H \leq 20.0$$

$$H/B \leq 10.0$$

At this time the following definitions are introduced:

Objective Function - The parameter which is to be minimized or maximized during optimization. The objective function always occurs on the left side of the equation unless it is also used as a design variable. An objective function may be either linear or nonlinear, implicit or explicit, but must be a function of the design variables.

Design Variable - Any parameter which the optimization process is allowed to change in order to improve the design. Design variables appear only on the right hand side of equations in the analysis program.

Inequality Constraint - Any parameter which must not exceed specified bounds for the design to be acceptable. Constraint functions always appear on the left side of equations. A constraint may be linear, nonlinear, implicit or explicit, but must be a function of one or more design variables.

Equality Constraint - Any parameter which must equal a specified value for the design to be acceptable. The same rules apply to equality constraints as inequality constraints.

Side Constraint - Any upper or lower bound placed upon a design variable. Side constraints are usually not included in the system of equations that comprise an analysis program. Instead they are usually included as part of the data input to the optimization program.

Analysis Code - The system of equations utilizing the design variables which are used to calculate the objective function and the constraints of a particular design problem.

The general optimization problem may thus be stated mathematically as:

Find the set of design variables \bar{X}_i where $i = 1, 2, \dots, n$ which will:

Minimize the objective function (Obj)

$$\text{Obj} = f(\bar{X})$$

Subject to:

Inequality constraints (G)

$$G_j(\bar{X}) \leq 0 \quad j = 1, 2, \dots, m$$

Equality constraints (H)

$$H_j(\bar{X}) = 0 \quad j = 1, 2, \dots, l$$

Side constraints

$$x_i^l \leq x_i \leq x_i^u \quad i = 1, 2, \dots, n$$

Returning to the cantilevered beam problem, it may be stated in the standard format as follows:

Let $X(1) = B$, $X(2) = H$, and $\text{Obj} = \text{Vol} = B \cdot H \cdot L$

Then minimize $\text{Obj} = \text{Vol}$

Subject to:

$$G(1) = \frac{\sigma_b}{20000} - 1 \leq 0$$

$$G(2) = \frac{v}{10000} - 1 \leq 0$$

$$G(3) = \delta - 1 \leq 0$$

$$G(4) = \frac{H}{B} - 10 \leq 0$$

With side constraints:

$$X(1)^L = 0.5$$

$$X(1)^U = 5.0$$

$$X(2)^L = 1.0$$

$$X(2)^U = 20.0$$

It is thus fairly simple and straightforward to perform an analysis on a particular beam for a given B and H. Successive analyses may be performed on the cantilevered beam by solving the above system of equations. It is desirable to automate the successive solutions and to direct the solutions such that each solution is a better design than the last. One approach for doing so, and the one used by DESOP is to proceed as follows: Start with initial values for B and H. Solve the above set of equations to find the objective function Obj and to see if any constraints are violated. A pseudo objective function is created to represent designs when constraints are violated. If a constraint is violated, a penalty is added to Obj to form a penalized objective function Opj. The gradient of the

penalized objective function at the initial design may be found by taking the first partial derivative of Op_j with respect to the design variables. The gradient of the penalized objective function defines the direction of steepest ascent. In the case of the cantilevered beam, it is desired to minimize the objective function; therefore, the greatest improvement in design may be achieved by moving in the negative gradient, or steepest descent direction. From the initial design point a search is performed in the steepest descent direction for the minimum value of Op_j in that direction. At the new minimum, the gradient of the penalized objective function is again determined and a search is performed in a conjugate direction until a second minimum is found. Successive iterations are performed until the gradient is found to be zero or each successive iteration produces a sufficiently small change in Op_j such that for all practical purposes the minimum has been found. At this time the penalty function is increased. If the design is in a region where there are no constraints violated an increase in the penalty function will not change the value of Op_j . If on the other hand the design is in an infeasible region where there are one or more constraints violated, Op_j will be increased, and the search for a new minimum will commence. If the minimum of the objective function exists in the infeasible region,

the minimum value for the objective function in the feasible region will be approached from the infeasible region as the penalty function is increased. The design improvement process will terminate when a zero gradient is found or successive iterations produce a sufficiently small change in the value of Opj and an increase in the penalty function causes no change in Opj .

The minimum thus reached by the optimization process is a minimum with respect to the penalized objective surface immediately surrounding the final design point. The optimization process cannot distinguish between local and global minimum points. It is thus good engineering practice to run several optimizations for a particular design problem from several different initial design points. If optimizations performed from different initial design points converge on the same minimum point, that point is probably a global minimum. If on the other hand two or more minimums are found, there may be local minimums located in the design space being considered and care must be taken to find the global minimum.

C. THE DESOP NUMERICAL OPTIMIZATION PROGRAM

The DEsktop Sequential unconstrained minimization technique Optimization Program was developed using the basic optimization approach outlined in Section II.A. A copy of the program is included in Appendix E. The major

program structure is shown in Figure 2. The following discussion will refer to Figure 2 and describe the major features of the program.

1. Basic Program Execution

The DESOP program begins execution when it is loaded, linked to the user's analysis subprogram, and the program is instructed to run by the OPCON program. The above actions are automatically performed by the OPCON program. DESOP is loaded into the computer by an overlay process. Therefore no variables can be directly transferred between the DESOP and OPCON programs. DESOP begins execution by reading the optimizer control variables and the design variables that were input using the OPCON program and saved to a mass storage device. The program then sets Icalc equal to one and evaluates the objective function and constraints at the initial design point. Icalc is a flag provided the user to key user specified output on the initial and final design analysis. DESOP will provide the user with a hard copy output of the initial design variables, the value of the constraints, the objective function and the penalized objective function. The user then has the option of continuing with the DESOP program to optimize his analysis subprogram or to return to the OPCON program to change one or more of the input parameters.

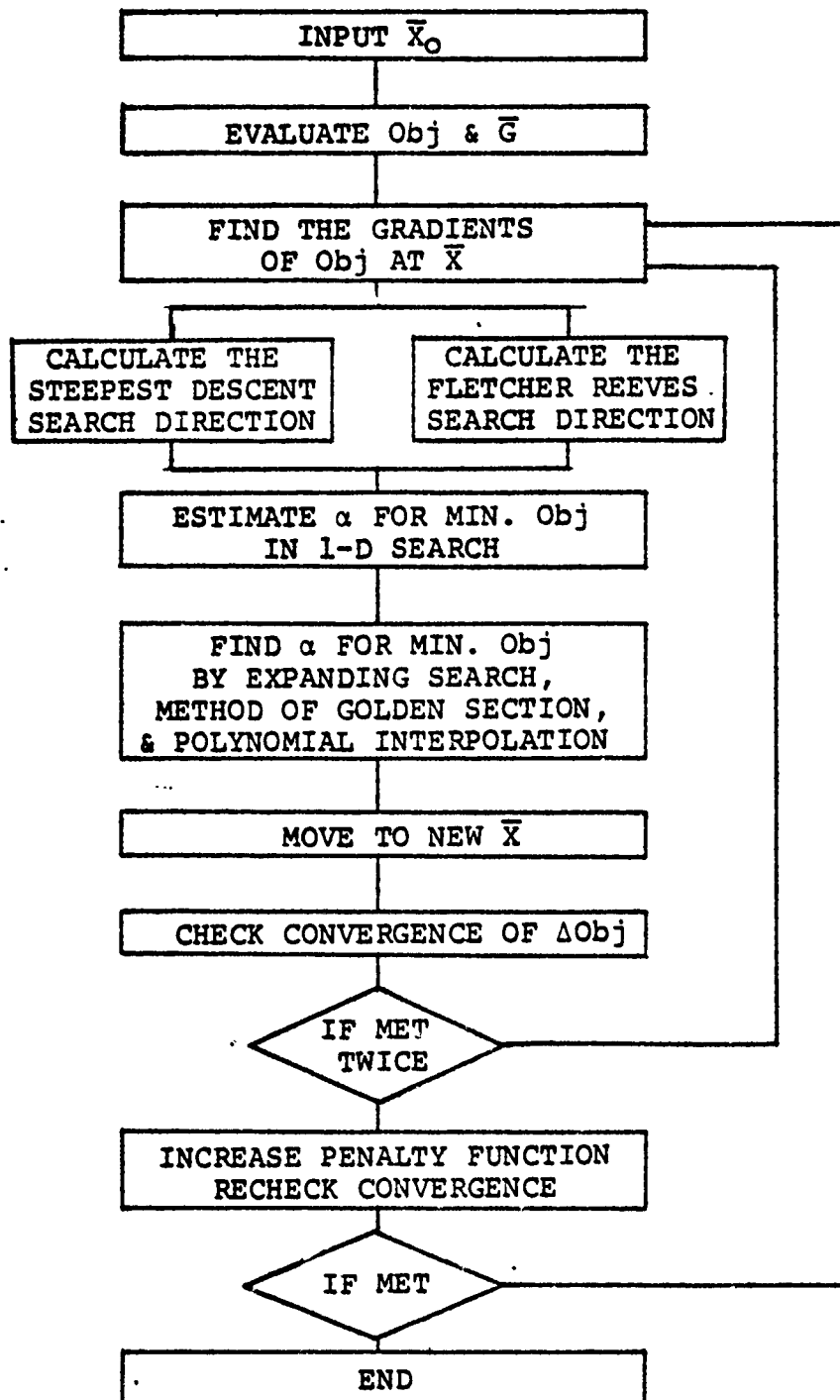


Figure 2. DESOP Flow Diagram

Proceeding with the optimization, there are two major loops in the optimization program. The outer loop increases the penalty function when the inner loop's convergence criteria have been met. A convergence test is then performed by the outer loop. If the convergence criteria is met, the optimization process is considered finished. If the convergence criteria for the outer loop is not met, program execution is returned to the inner loop. The inner loop performs successive iterations searching for the minimum of the penalized objective function with no increase in the penalty function taking place. When the inner loop's convergence criteria have been met program execution is transferred to the outer loop.

Execution of the program while in the inner loop proceeds as follows: First, the gradient of the penalized objective function is calculated by subroutine GRAD. The program then computes a search direction using either a steepest descent method or the method of conjugate directions developed by Fletcher and Reeves [Ref. 1]. Once a search direction is established the optimizer attempts to locate the minimum value of the penalized objective function in the search direction. This process is referred to as the one-dimensional search and is illustrated in Figure 3. The efficiency and accuracy to which the one-dimensional search for the minimum of the penalized objective function

is accomplished, is the key to successful sequential unconstrained minimization technique numerical optimization. The one-dimensional problem may be expressed in terms of the penalized objective function, Op_j , and the amount of movement, α , in the search direction, \bar{S} . First the slope of Op_j with respect to α is calculated. An initial "guess" of how far to move is made using subroutine ALPGES. The α which corresponds to the minimum value of Op_j in the one-dimensional search is then calculated using subroutine ALPBND and subroutine QUEBIC. The minimum value of Op_j thus found is then compared to the previous value of Op_j for convergence using subroutine CONVRG. If convergence is not met, execution returns to the start of the inner loop. If convergence is met, execution returns to the outer loop.

When the convergence criteria have been met for both the inner and outer loops, the program proceeds to set ICALC to three as a flag for user generated output for the final design. DESOP then provides the user with a hard copy output of the final design variables, objective function value, penalized objective value, constraint values, the number of inner loop iterations, the number of times the analysis subprogram was called and the final value of the penalty function. The OPCON program is then overlayed over the DESOP program and program execution is returned to the OPCON program.

2. Finding the Search Direction

The first step in finding the search direction, \bar{S} , is to determine the slope of Opj at the present design point. The forward finite difference method is used where:

$$\frac{\partial F}{\partial X_i} = \frac{F(X_i + \Delta X_i) - F(X_i)}{\Delta X_i} = -S_i$$

$i = 1, 2, \dots, Ndv$

As $\partial F / \partial X_i$ gives the direction of positive slope, the search direction is the negative of $\partial F / \partial X_i$. The first search is performed using the steepest descent as found above using the following relation:

$$X_i' = X_i + \alpha S_i$$

where alpha is the distance moved in the \bar{S} direction. When a minimum is obtained along the direction of steepest descent, a new Fletcher-Reeves conjugate search direction [Ref. 1] is calculated at the new Design point using the following relations:

$$S_i' = \frac{\partial F}{\partial X_i} + B S_i$$

$$B = \frac{\sum_{i=1}^{NdV} \left[\frac{\partial F'}{\partial X_i} \right]^2}{\sum_{i=1}^{NdV} \left[\frac{\partial F}{\partial X_i} \right]^2}$$

where the prime denotes values for the present iteration and the non-prime variables indicate values for the previous

iteration. A one-dimensional search is then performed in the new search direction. Searches are continued using the conjugate direction method for $N_{dv} + 1$ iterations, where N_{dv} is the number of design variables. The search process is then restarted using the steepest descent method. The reason for incorporating the conjugate search method is that the steepest descent method when traversing a design surface with a curved valley will tend to zigzag from one side of the design surface valley to the other making very little progress as is illustrated in Figure 4. The conjugate direction method is much more efficient in traversing such a design surface. However, as the conjugate direction method is additive upon previous searches, it has a tendency to decrease in effectiveness with each successive search owing to the accumulation of numerical "noise." For that reason the search process is restarted with the steepest descent method every $N_{dv} + 1$ iterations, or when the conjugate direction predicts a positive slope. The search direction is normalized to avoid inaccuracies caused by numerical ill-conditioning.

3. Estimating an Initial Value for Alpha

The initial estimate for alpha is made in the following manner: First, the slope of Op_j in the search direction is calculated as the sum of each of the products of the gradients times the search direction. Then the slope of Op_j in the search direction is divided by the value

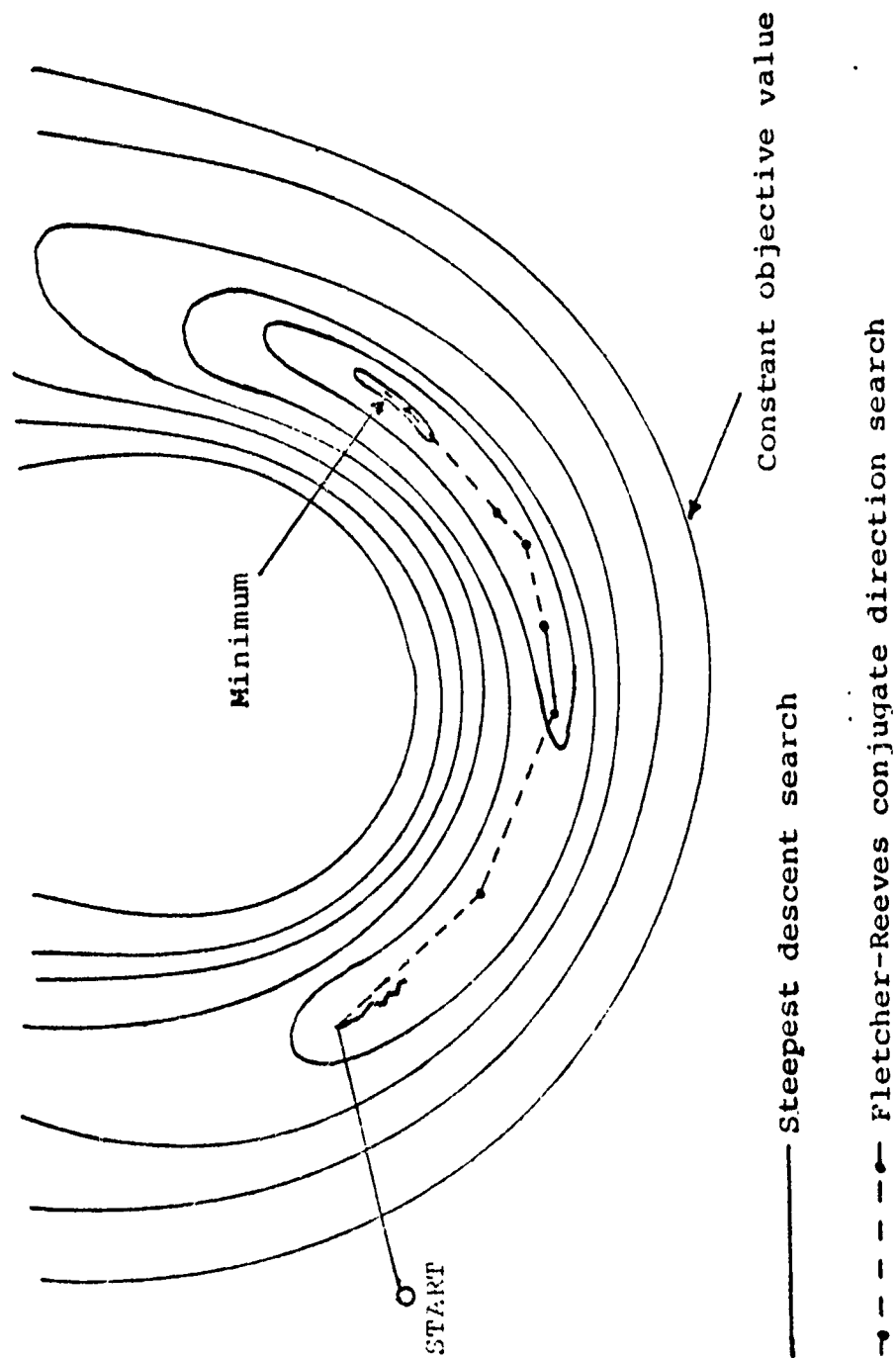


Figure 4. Steepest Descent and Conjugate Direction Search in a Two-Dimension Design Space.

of Opj . This value is then multiplied by an improvement percentage in Opj . This first estimate is then applied to a series of conditional tests to determine the validity of the estimate with respect to the slope of Opj and the magnitude of the design variables. Lastly, the estimate for alpha is checked to see if it violates any side constraints. If it does, the value of the estimate for alpha is reduced until the side constraints are no longer violated.

4. Calculating Alpha

The calculation of alpha is the most critical algorithm in the DESOP program in providing reliable optimizer operation. The ability to accurately and efficiently find the minimum of the penalized objective function in the one-dimensional search affects directly the operation of the optimizer. Figure 5 illustrates the zigzag phenomenon which occurs if alpha is not accurately found. The zigzag phenomenon is caused by the fact that the optimizer in performing the forward finite difference for calculating the search direction perturbs the design vector a very small amount. As such the optimizer can only "see" the design surface that is immediately adjacent to the design point. Therefore, if the minimum is not found in the one-dimensional search, the optimizer will converge very slowly on the minimum.

There are two major sections to the ALPBND subroutine. The first section attempts to find the minimum value of Opj

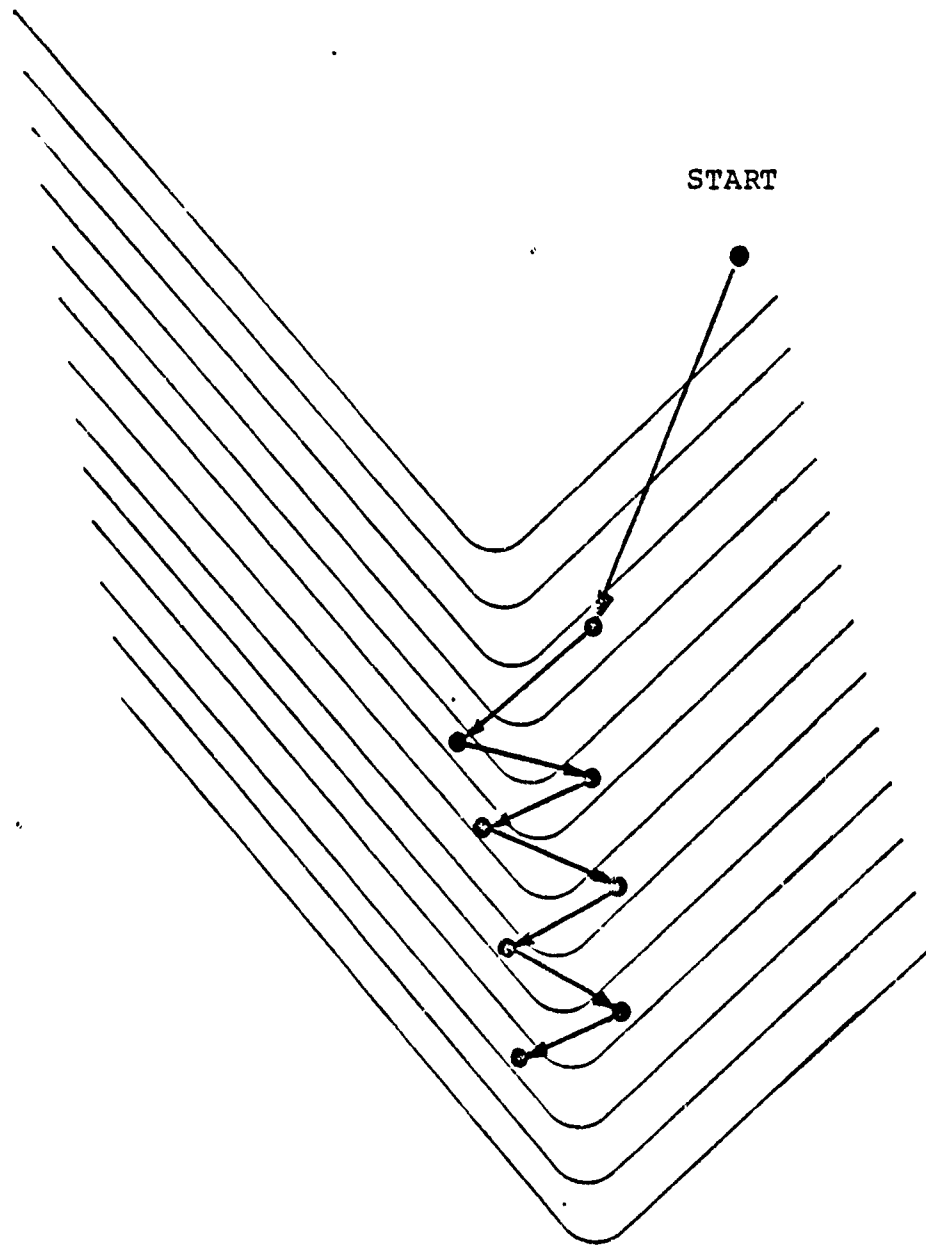


Figure 5. The Zigzag Phenomenon

using an expanding search technique. The first move is the amount predicted by the ALPGES subroutine. If the minimum is not bracketed by the first move, additional moves are made. Each move is larger than the last. The size of the move is increased each time by an amount equal to the size of the last move divided by the lower Golden Section fraction, where the Golden Section fractions are:

$$F_1 = \frac{3 - \sqrt{5}}{2}$$

$$F_2 = \frac{\sqrt{5} - 1}{2}$$

The lower Golden Section fraction, F_1 , is used so that the interval will be consistent with the Golden Section search in the second section of the ALPBND subroutine. The expanding search is continued until the minimum value of the objective function has been bracketed.

Once the minimum is bracketed, a Golden Section search is performed to reduce the bracketing interval on the minimum by an amount such that when the two end points of the interval are taken with two points internal to the interval and a cubic is passed through the four points, the cubic will accurately predict the minimum of the penalized objective function. Himmelblau in [Ref. 2] states that the Golden Section search method of reducing the interval around the minimum of Q_{pj} is the most effective of the reducing techniques studied. Golden Section search is based

on the splitting of a line into two segments known in ancient times as the "Golden Section." The ratio of the whole line to the larger segment is the same as the ratio of the larger segment to the smaller segment. The two Golden Section fractions are employed to split the interval bracketing the minimum as shown in Figure 3. Once the interval has been split, the two values of Op_j corresponding to the internal points are compared to find the larger of the two. The internal point with the larger value of Op_j will become the new end point for the interval, the remaining interior point will by the fact that it was determined by a Golden Section fraction, be equal to the point determined by the other Golden Section fraction. Thus, only one new point must be calculated to continue the Golden Section search. The search is continued in this manner until the vertical separation of the two end points with respect to the interior points is less than one percent. The four values of the penalized objective function corresponding to the four Golden Section search points are then sent to a cubic interpolator. The cubic interpolator will return a value for α to predict the minimum of the penalized objective function, and the minimum of the cubic function that the interpolator has created. The subroutine ALPBND will then test the predicted minimum with the minimum found at the predicted α . If there is less than a tenth of

one percent difference between the two values of the objective function, the point predicted by the cubic interpolator will be accepted as the minimum and program execution will return to the main program. If the predicted minimum is not sufficiently close to the minimum at the predicted alpha, another Golden Section search will be performed to reduce the interval and better localize the minimum. The four points from the reduced interval will then be sent to the cubic interpolation subroutine. This process will continue until either the test for the minimum is positive or the interval has been reduced to less than $1E-12$. Program execution will then return to the main program.

5. Subroutine QUEBIC

Subroutine QUEBIC is used to estimate the alpha at which Opj is a minimum based on four point cubic interpolation. If the function more closely resembles a quadratic than a cubic, a three point quadratic interpolation is performed using the three points which bracket the minimum. If the predicted minimum is outside the interval spanned by the two end points again a quadratic interpolation is performed. If the minimum still lies outside the two end points, the analysis returns to subroutine ALPBND, the interval bracketing the minimum is reduced, and program execution returns to QUEBIC.

6. Convergence of the Penalized Objective Function

The penalized objective function is tested for convergence at the end of each inner loop and again at the end of the outer loop in the main program. Convergence is tested by calling subroutine CONVRG. There are two criteria used for testing for convergence. The first tests the relative difference of the value of Opj from the present iteration with the value of Opj from the last iteration. The second method tests the absolute difference of the two values. The second method is employed for cases when the value of the penalized objective function approaches zero. When convergence has been met on two successive iterations, the penalty function is increased by an amount specified by the user in the executive OPCON program. The penalized objective function is again tested for convergence. If convergence is still met, the optimizer considers the present value of the penalized objective function to be a minimum, noting again that numerical optimization programs cannot differentiate between local and global minimums.

7. The Penalty Function

The purpose of the penalty function is to increase the value of the objective function when the design is in an infeasible region. The infeasible region is that region where one or more design constraints are violated. When a constraint is violated, the value of the particular constraint,

G_j , is positive. The objective function is then penalized as follows:

$$Opj = Obj + R \cdot G_j \cdot E$$

where:

R - a multiplication constant

E - an exponent constant

This type of penalty function, one where the penalty is applied after the design leaves the feasible region, is known as an exterior penalty function. The exterior type of penalty function was chosen over other types, such as the interior or extended interior penalty function. If a function is discontinuous within the design space being studied, numerical difficulties may be encountered which make performing an optimization of the design difficult.

D. USE OF THE DESOP NUMERICAL OPTIMIZATION PROGRAM

Once the analysis subprogram has been written and SAVED, the user may perform a numerical optimization of the design analysis. Figure 11 shows the basic relationships between the OPCON and DESOP programs and the user supplied ANALIZ subprograms. Note that the DESOP program overlays the OPCON program after all data has been input. To begin, LOAD OPCON and press run. Through a series of self-explanatory menus, the user will be prompted to input control variables, design variables and execute the DESOP program. The following menus appear in the OPCON program.

1. INTRODUCTION - A brief introduction stating the purpose of the OPCON program.
2. NEW OR EXISTING ANALYSIS PROGRAM - If this is the first time that a particular analysis subprogram has been run on the tape or disk being used, or if the files from a subsequent run have been deleted, the user must enter the response for a new analysis subprogram. For existing programs, OPCON will read data from the existing data file. The data read will be that from the subsequent run of the particular analysis subprogram.
3. NAME THE ANALIZ SUBPROGRAM - The user will input the name under which the analysis subprogram he wishes to use was saved. If this is a new analysis subprogram OPCON will create files for saving the data input during the execution of OPCON.

4. OPTIMIZER SELECTION - At the present time there is only one optimization program available. It is hoped that at some future date additional numerical optimization programs will be added to the optimization package. OPCON has been developed to interface with multiple numerical optimization programs. Details for linking other numerical optimization programs to OPCON are included as comments in the OPCON listing which may be found in Appendix D.

5. INPUT NDV AND NCON - For a new analysis subprogram the user will be asked to input the number of design variables, NDV, and the number of constraints in the analysis subprogram, NCON.

6. INPUT CHECK OF COMMON CONTROL VARIABLES - A menu of the optimizer control parameters common to DESOP, Feasible Direction type and other future optimization programs is displayed. The menu displays the variable name, its minimum, maximum, default and present value. The variables displayed are:

NDV - The number of independent design variables used in the analysis code.

NCON - The number of constraints in the design analysis subprogram.

IPRINT - A print control used in the optimization program to display intermediate results. Positive values entered will print on the CRT. Negative values entered

will print on the thermal printer. If a zero is entered there will not be a hard copy output of the initial and final results of the optimization program. IPRINT = 0 is to be used when debugging an analysis subprogram to conserve thermal paper.

+1 - Print initial and final optimization information.

+2 - Print above plus the objective function and penalized objective function on each iteration.

+3 - Print above plus the constraint values, search direction vector and move parameter alpha on each iteration.

+4 - Print above plus gradient information on each iteration.

+5 - Print above plus each proposed design vector and the penalized objective function during the one-dimensional search on each iteration.

+6 - Debugging aid for optimizer development. DESOP will pause after each major operation is performed during the optimization process.

DELFUN - The minimum absolute change in the objective function to indicate convergence of the optimization process.

DABFUN - The minimum absolute change in the objective function to indicate convergence of the optimization process.

ITMAX - The maximum number of inner loop (unconstrained minimizations) without increasing the penalty function.

ICNDIR - The conjugate direction restart parameter. Every ICNDIR inner loop iterations a steepest descent search is performed. It is recommended that ICNDIR be set equal to $NDV + 1$.

FDCH - The relative change in the design variables for calculating finite difference gradients.

FDCHM - The minimum absolute step in finite difference gradient calculations.

ABOBJ1 - The expected fractional change in the objective function for the first estimates of the step size to be taken in the one-dimensional search.

ALPHAX - The maximum fractional change in any design variable for the first estimate of the step size to be taken in the one-dimensional search.

7. INPUT CHECK OF THE DESOP CONTROL PARAMETERS - A menu of the optimizer control parameters for the DESOP optimization program is displayed. The menu will display the variable name, its maximum, minimum, default and present value. The variables displayed are:

IRMAX - The maximum number of times that the penalty parameter will be increased.

RZ - The starting value of the penalty parameter.

RMULT - The amount by which RZ is multiplied each time that it is increased.

EXPG - The amount by which a violated constraint value is raised to an exponent, EXPG.

NSCAL - A design variable auto-scaling control.

0 - No scaling of the design variables is performed by DESOP.

1 - The design variables are scaled every ICNDIR iteration.

9. INPUT DESIGN VARIABLES AND SIDE CONSTRAINTS - A menu of the initial design variables and constraints will be displayed for an existing analysis subprogram. If this is a new analysis subprogram, the user will be asked to enter the initial values of the design variables and any side constraints on the design variables.

A hard copy printout of the optimizer control parameters, design variables and side constraints will then be presented to the user to check to ensure that the above information has been entered correctly. The user then has the option to return to the input routine and make changes to the above information or to continue and optimize his design. If the user chooses to continue, OPCON will overlay the optimization program on OPCON beginning at line C2. The analyze subprogram specified will then be linked to the end of the DESOP program. The entire program will then be STORED under the program name OP. The OP program will then be loaded with

execution beginning at line OPT1. The storing and reloading process allows the OP program to be called and run as a separate program for debugging purposes. At the completion of the optimization process, the optimizer program will reload OPCON and return execution to the OPCON program. A menu will be displayed welcoming the user back to the OPCON program giving him the following options: to optimize again using the same ANALIZ subprogram, to optimize again using a different ANALIZ subprogram, or to terminate the program.

APPENDIX D

OPCON Program Listing

```

100 *****
110 *
120 *
130 *
140 *
150 *
160 *
170 *
180 *
190 *
200 *****
210 *
220 *
230 *
240 *
250 *
260 *
270 *
280 *
290 *
300 *****
310 *
320 *
330 *
340 *
350 *
360 *
370 *
380 *
390 *
400 *

      OPCON

      THE EXECUTIVE PROGRAM FOR PERFORMING NUMERICAL
      OPTIMIZATION ON THE HP 9845A COMPUTER

      by W. B. COLE
      NAVAL POSTGRADUATE SCHOOL, MONTEREY, CALIFORNIA
      1980

      *****
      FUNCTIONS :
      1. INPUT AND STORAGE OF CONTROL PARAMETERS FOR THE OPTIMIZERS USED
      2. INPUT AND STORAGE OF THE DESIGN VARIABLES AND SIDE CONSTRAINTS
         ON THE OPTIMIZERS USED
      3. CONTROL OF THE OPTIMIZATION PROCESS THROUGH THE USE OF OVERLAYS

      -----
      NOTE: OPCON was written to control multiple optimization programs. At
            the present time DESOP is the only optimizer working. A Feasible
            Directions optimizer has been partially written and debugged. At
            the present time OPCON has been written to accept the control
            parameters for the Feasible Direction optimization program.
      -----
      ----- CONTROL SECTION -----
      -----
      COM Globcm(50),P$,D$,Analiz$
      GOTO C7

```

```

410 ! -----
420 C1: ! ----- CONTROL FOR SUMT OPTIMIZER -----
430 ! -----
440 PRINTER IS 16
450 PRINT PAGE
460 PRINT LINK(5), TAB(10), " LINKING SUMT OPTIMIZER AND ";Analiz$;" ROUTINE."
470 LINK Op$,C2
480 LINK Analiz$,Analiz1
490 RE-STORE "OP"
500 LOAD "OP",Opt1
510 ! -----
520 C2: ! ----- ATTACHMENT POINT FOR OPTIMIZER -----
530 ! -----
540 ! -----
550 ! -----
560 C7: ! ----- INTRODUCTION -----
570 ! -----
580 PRINTER IS 16
590 PRINT PAGE
600 PRINT "
610 PRINT LINK(2), "OPCON IS THE CONTROL PROGRAM FOR PERFORMING NUMERICAL OPTIM
    IZATION ON "
620 PRINT LINK(1), "THE HP 9845 DESKTOP COMPUTER."
630 PRINT LINK(2), "THE FUNCTIONS OF OPCON ARE : "
640 PRINT LINK(1), "
    1. THE INPUT AND STORAGE OF CONTROL PARAMETERS.
    2. THE INPUT AND STORAGE OF DESIGN VARIABLES."
    3. CONTROL OF THE OPTIMIZATION PROCESS THROUGH PROGRAM
    OVERLAYS."
650 PRINT "
660 PRINT "
670 DISP " PRESS 'CONT' "
680 PAUSE
690 GOTO C10

```

```

700 ! -----
710 C6: ! ----- RETURN FROM OPTIMIZATION -----
720 ! -----
730 PRINTER IS 16
740 PRINT PAGE
750 PRINT "
760 PRINT LINK(1), "WELCOME BACK TO 'OPCON'. YOU NOW HAVE SEVERAL AVAILABLE OPT
IONS."
*** WELCOME BACK ***
770 PRINT LINK(1), " 1. OPTIMIZE THE ";Analyze;" FUNCTION."
780 PRINT LINK(1), " 2. OPTIMIZE A DIFFERENT ANALYZE FUNCTION."
790 PRINT LINK(1), " 3. TERMINATE THE PROGRAM."
800 INPUT " INPUT YOUR CHOICE : 1,2 OR 3 .", Ch
810 IF Ch=1 THEN Prog1=1
820 IF Ch=1 THEN GOTO C13
830 IF Ch=2 THEN Prog1=0
840 IF Ch=2 THEN GOTO C12
850 IF Ch=3 THEN PRINT PAGE
860 IF Ch=3 THEN PRINT "
870 IF Ch=3 THEN GOTO 299
880 GOSUB Err
890 GOTO C8
900 ! -----
910 C9: ! ----- RETURN FROM END OF INPUT ROUTINE -----
920 ! -----
930 PRINTER IS 16
940 PRINT PAGE
950 PRINT "DO YOU STILL WISH TO OPTIMIZE THE ";Analyze;" FUNCTION?"
960 INPUT " ( 1 - YES : 0 - NO )", Ch
970 IF Ch=0 THEN C10
980 IF Ch=1 THEN Para9
990 GOSUB Err
1000 GOTO C9

```

```

1010 ! -----
1020 C10: ! ----- CONTROL PARAMETER INPUT -----
1030 ! -----
1040 DIM Lmin(4), Ladd(4), P(50,4), Param$(50), X(30), V1b(30), Vub(30)
1050 DIM S$(40), Params(50)
1060 PRINT IS 16 ! (CRT)
1070 PRINT PAGE
1080 ! -----
1090 C11: ! ----- NEW OR EXISTING PROGRAM ? -----
1100 ! -----
1110 PRINT LIN(3), TAB(17), "IS THIS A NEW OR EXISTING PROGRAM ?"
1120 INPUT " INPUT : ( NEW = 0 , EXISTING = 1 ) ", Progl
1130 ! -----
1140 C12: ! ----- NAME THE ANALIZE PROGRAM -----
1150 ! -----
1160 PRINT PAGE
1170 PRINT LIN(3), TAB(10), "WHAT IS THE NAME OF THE ANALIZE PROGRAM ?"
1180 INPUT " INPUT THE NAME : ", Analiz$
1190 DISP "CREATING NEW FILES FOR "; Analiz$
1200 P$="P"
1210 D$="D"
1220 P$(2,61)=Analiz$
1230 D$(2,61)=Analiz$
1240 IF Progl=1 THEN GOTO 1290
1250 ON ERROR GOTO Err1
1260 CREATE P$,4
1270 CREATE D$,3
1280 OFF ERROR
1290 PRINT PAGE
! ASSIGN PARAMETER AND DESIGN VARIABLE
! FILE NAMES TO MATCH THE ANALIZE
! ROUTINE.
! IF THIS IS A NEW PROGRAM, CREATE THE

```

```

1300 ! -----
1310 C13: ! ----- OPTIMIZER SELECTION -----
1320 ! -----
1330 PRINT LIN(3),TAB(5),"WHICH OF THE FOLLOWING OPTIMIZERS DO YOU WISH TO USE ?"
1340 PRINT LIN(1),TAB(5),"1. SEQUENTIAL UNCONSTRAINED OPTIMIZATION. DESOP"
1350 ! PRINT LIN(1),TAB(5),"2. FEASIBLE-DIRECTION OPTIMIZATION."
1360 PRINT LIN(3)," AT THE PRESENT TIME DESOP IS THE ONLY OPTIMIZATION PROGRAM AVAILABLE."
1370 INPUT " INPUT THE OPTIMIZER NUMBER : ",Prog2
1380 IF Prog2=1 THEN Op$="DESOP"
1390 IF Prog2=2 THEN Op$="OPT-2"
1400 IF Prog2=1 THEN GOTO Para10
1410 ! -----
1420 C14: ! ----- INPUT INITIAL VALUE FOR NDV -----
1430 ! -----
1440 Paramf(1)="NDV"
1450 P(1,1)=1
1460 P(1,2)=30
1470 P(1,3)=0
1480 PRINT PAGE
1490 PRINT LIN(3),TAB(5)," INPUT THE NUMBER OF DESIGN VARIABLES ( NDV ) "
1500 PRINT TAB(5),"MIN = ",P(1,1)
1510 PRINT TAB(5),"MAX = ",P(1,2)
1520 INPUT " NDV = ? ",P(1,4)
1530 NDV=P(1,4)
1540 IF (P(1,4))>P(1,1) AND (P(1,4)<=P(1,2)) THEN Para10
1550 GOSUB Err
1560 GOTO 1480
1570 Para10: ! CONTINUE

```



```

1580 ! -----
1590 ! ----- CONTROL PARAMETER DATA -----
1600 ! -----
1610 DATA 2,10
1620 DATA NCON,0,20,0
1630 DATA IPRINT,-5,6,0
1640 DATA DELFUN,0.0,0.1,0.001
1650 DATA DABFUN,0.0,0.1,0.001
1660 DATA ITMAX,1,100,20
1670 DATA ICNDIP,2,21,5
1680 DATA FDCH,1E-5,0.1,0.001
1690 DATA FDCHM,1E-5,0.1,0.0001
1700 DATA AB0BJ1,0.01,0.5,0.1
1710 DATA ALPHA,0.01,0.5,0.1
1720 ! -----
1730 ! ----- OPTIMIZER #2 CONTROL PARAMETERS -----
1740 ! -----
1750 DATA 20,10
1760 DATA IPBEG,0,1,0
1770 DATA CT,0,1,0.1
1780 DATA CTMIN,-0.01,0,-0.004
1790 DATA CTL,0,1,0.1
1800 DATA CTLMIN,-0.1,0,-0.001
1810 DATA PHI,1,100,5
1820 DATA THETA,0,10,1
1830 DATA ITRM,1,5,3
1840 DATA CG,0,1,0
1850 DATA NCF,0,40,0

```

```

1860      ! ----- OPTIMIZER #1 CONTROL PARAMETERS -----
1870      !
1880      !
1890      DATA 40,5
1900      DATA IRMAX,1,30,10
1910      DATA RZ,.0001,9999,2
1920      DATA RMULT,0.001,1000,2
1930      DATA EXPG,1,10,2
1940      DATA NSCAL,0,1,1
1950      FOR K=1 TO 3
1960          READ Lmin(K),Ladd(K)
1970          FOR I=Lmin(K) TO Lmin(K)+Ladd(K)-1
1980              READ Param$(I),P(I,1),P(I,2),P(I,3)
1990              NEXT I
2000          NEXT K
2010      IF Prog1=1 THEN GOTO P3      ! (CONTINUE)
2020      FOR I=2 TO 50
2030          P(I,4)=P(I,3)
2040      NEXT I
2050      ! ----- IF EXISTING PROGRAM - READ EXISTING VALUES -----
2060      P3:  !
2070      !
2080      IF Prog1=0 THEN Para9
2090      Param$(1)="NDV"
2100      DISP "READING EXISTING CONTROL PARAMETERS AND DESIGN VARIABLES."
2110      ASSIGN #1 TO P4
2120      ASSIGN #2 TO D$
2130      FOR J=1 TO 3
2140          READ #1,J
2150          K=Lmin(J)-(J=1)
2160          K1=K+Ladd(J)-1+(J=1)
2170          FOR I=K TO K1
2180              READ #1;P(I,4)
2190          NEXT I
2200          NEXT J
2210      Ndu=P(1,4)

```

```

2220 ! ----- READ EXISTING DESIGN VARIABLES -----
2230 !
2240 !
2250 READ #2,1
2260 FOR I=1 TO Ndu
2270 READ #2;X(I)
2280 NEXT I
2290 READ #2,2
2300 FOR I=1 TO Ndu
2310 READ #2;V1b(I),Vub(I)
2320 NEXT I
2330 Para9: ! CONTINUE
2340 !
2350 ! ----- INPUT CHECK -----
2360 !
2370 K=1
2380 PRINT PAGE
2390 PRINT TAB(10),"INPUT CHECK OF COMMON CONTROL PARAMETERS"
2400 PRINT LIN(1)
2410 PRINT "REF #  PARAMETER      MINIMUM      MAXIMUM      RECOMMENDED"
2420 PRINT "-----"
2430 IMAGE 4X,"1",3X,6A,4X,M4D.4D,4X,M4D.4D,8X,"*****",4X,M4D.4D
2440 PRINT USING 2420;Param$(1),P(1,1),P(1,2),P(1,4)
2450 IMAGE 4X,"2",3X,6A,4X,M4D.4D,4X,M4D.4D,8X,"*****",4X,M4D.4D
2460 PRINT USING 2440;Param$(2),P(2,1),P(2,2),P(2,4)
2470 FOR I=3 TO Ladd(1)+1
2480 IMAGE 3X,DD,3X,6A,4X,M4D.4D
2490 PRINT USING 2470;I,Param$(I),P(1,1),P(1,2),P(1,3),P(1,4)
2500 NEXT I
2510 PRINT LIN(1)," NOTE : IPRINT = 6 IS DEBUG MODE, THERE IS NO HARDCOPY OU
TPUT !"
2520 IF Ic=1 THEN GOTO 2560
2530 INPUT "DO YOU WISH TO MAKE ANY CHANGES? ENTER REF# OR 0 FOR NONE.",Ch
2540 IF Ch=0 THEN Para11
2550 IF (Ch<0) OR (Ch>Ladd(K)+1) THEN GOSUB Err
IF (Ch<0) OR (Ch>Ladd(K)+1) THEN GOTO 2380

```

```

2550 DISP "INPUT THE CHANGE TO ";Param$(Ch);
2570 INPUT Pch
2580 IF (Pch)=P(Ch,1) AND (Pch<=P(Ch,2)) THEN Para13
2590 GOSUB Err
2600 Ie=1
2610 GOTO 2380
2620 Para13: P(Ch,4)=Pch
2630 Ie=0
2640 GOTO 2380
2650 Para12: ! ( INPUT ERROR )
2660 GOTO 2380
2670 ! -----
2680 Para11: ! ----- INPUT CHECK FEASIBLE-DIRECTION -----
2690 ! -----
2700 GOTO Para15
2710 PRINT PAGE
2720 IF Prog2<>1 THEN Para15
2730 K=2
2740 PRINT TAB(5); "INPUT CHECK - USABLE-FEASIBLE CONTROL PARAMETERS"
2750 PRINT LIN(1);
2760 PRINT "REF # PARAMETER MINIMUM MAXIMUM RECOMMENDED"
2770 PRINT "PRESENT"
2780 FOR I=Lmin(K) TO Lmin(K)+Ladd(K)
2790 IMAGE 3X,DD,3X,6A,4(4X),M4D.4D)
2800 PRINT USING 2780;I,Param$(I),P(I,1),P(I,2),P(I,3),P(I,4)
2810 NEXT I
2820 IF Ie=1 THEN Para14
2830 PRINT LIN(2); "DO YOU WISH TO MAKE ANY CHANGES ?"
2840 INPUT " ( INPUT : REF # -OR- 0 FOR NONE )",Ch
2850 IF Ch=0 THEN Para15
2860 IF (Ch<Lmin(K)) OR (Ch>Lmin(K)+Ladd(K)) THEN COSUB Err
2870 IF (Ch<Lmin(K)) OR (Ch>Lmin(K)+Ladd(K)) THEN GOTO 2710
2880 Para14: DISP "INPUT THE CHANGE TO ";Param$(Ch);
2890 INPUT Pch
2900 IF (Pch)=P(Ch,1) AND (Pch<=P(Ch,2)) THEN Para17
2910 GOSUB Err
2920 Ie=1

```

```

2920 GOTO 2710
2930 Para17: P(Ch,4)=Pch
2940 Ie=0
2950 GOTO 2710
2960 I
2970 Para15: I ----- INPUT CHECK DESOP -----
2980 I
2990 PRINT PAGE
3000 IF Prog2<>2 THEN Para25
3010 K=3
3020 PRINT TAB(15),"INPUT CHECK - 'SUMT' CONTROL PARAMETERS"
3030 PRINT LIN(1)
3040 PRINT "REF # PARAMETER MINIMUM MAXIMUM RECOMMENDED"
3050 PRINT
3060 FOR I=Lmin(K) TO Lmin(K)+Ladd(K)-1
3070 IMAGE 3X,DD,3X,6A,4(4X,M4D.4D)
3080 PRINT USING 2780;I,Params(1),P(1,1),P(1,2),P(1,3),P(1,4)
3090 NEXT I
3100 IF Ie=1 THEN Para14
3110 PRINT LIN(2),"DO YOU WISH TO MAKE ANY CHANGES?"
3120 INPUT " ( INPUT : REF # -OR- 0 FOR NONE )",Ch
3130 IF Ch=0 THEN Para25
3140 IF (Ch<Lmin(K)) OR (Ch>Lmin(K)+Ladd(K)) THEN GOSUB Err
3150 IF (Ch<Lmin(K)) OR (Ch>Lmin(K)+Ladd(K)) THEN GOTO 2990
3160 Para24: PRINT LIN(1),"INPUT THE CHANGE TO ";Params(Ch)
3170 INPUT Pch
3180 IF (Pch>=P(Ch,1)) AND (Pch<=P(Ch,2)) THEN Para27
3190 Ie=1
3200 GOTO 2990
3210 Para27: P(Ch,4)=Pch
3220 Ie=0
3230 GOTO 2990
3240 Para25: I CONTINUE
3250 IF Prog1=1 THEN Sidein6
3260 I1=0

```

EXISTING PROGRAM GOTO INPUT CHECK

```

3260 PRINT PAGE
3270 PRINT TAB(15), "INPUT THE INITIAL VALUES FOR THE DESIGN VARIABLES"
3280 PRINT LIN(1)
3290 GOSUB Sidein
3300 PRINT PAGE
3310 PRINT "END OF INPUT ROUTINE"
3320 ! -----
3330 Sav: ! ----- SAVE INPUTS -----
3340 ! -----
3350 PRINT PAGE
3360 Iprint=P(3,4)
3370 IF Iprint=6 THEN S1
3380 PRINTER IS 0
3390 PRINT LIN(3)
3400 PRINT "-----"
3410 PRINT LIN(3)
3420 PRINT "ANALYZE PROGRAM : ";Analizf
3430 IF Prog2=1 THEN PRINT LIN(2), "OPTIMIZER USED : DESOP"
3440 ! : IF Prog2=2 THEN PRINT LIN(2), "OPTIMIZER USED : FEHISIBLE-DIRECTION
3450 PRINT LIN(2), "INPUT FOR OPTIMIZATION : "
3460 PRINT LIN(1)
3470 S1: DISP "SAVING INPUT PARAMETERS."
3480 ASSIGN #1 TO P$
3490 ASSIGN #2 TO D$
3500 PRINT #1,4;Ladd(1)+1,Ladd(2),Ladd(3)
3510 FOR J=1 TO 3
3520 READ #1,J
3530 K=Lmin(J)-(J=1)
3540 K1=K+Ladd(J)-1+(J=1)
3550 FOR I=K TO K1
3560 PRINT Paramf(1); "=";P(I,4),
3570 PRINT #1;P(I,4)
3580 NEXT I
3590 PRINT #1;END
3600 NEXT J

! J = 1 COMMON CONTROL PARAMS
! J = 2 U/F CONTROL PARAMETERS
! J = 3 SUMT CONTROL PARAMS

! PUT PARAMS INTO MASS STORAGE

```

```

3610 ! -----
3620 ! ----- SAVE THE DESIGN VARIABLES -----
3630 ! -----
3640 DISP "SAVING DESIGN VARIABLES"
3650 PRINT LIN(1)
3660 READ #2,1
3670 FOR I=1 TO Ndv
3680 PRINT "X(";I;") = ";X(I),
3690 PRINT #2;X(I)
3700 NEXT I
3710 PRINT #2;END
3720 READ #2,2
3730 PRINT LIN(1)
3740 FOR I=1 TO Ndv
3750 PRINT "VLB("&VAL$(I)&" ) = ";Vlb(I);TAB(40),"VUB("&VAL$(I)&" ) = ";Vub(I)
3760 PRINT #2;Vlb(I),Vub(I)
3770 NEXT I
3780 PRINT #2;END
3790 DISP "CHECK YOUR INPUT - PRESS 'CONT' TO CONTINUE."
3800 BEEP
3810 PAUSE
3820 GOTO P20
3830 ! -----
3840 Sidein: ! ----- DESIGN VARIABLE INPUT -----
3850 ! -----
3860 Addcon=0
3870 FOR I=1 TO Ndv
3880 GOSUB Sidein1
3890 NEXT I
3900 I=0
3910 Sidein2: INPUT "DO YOU WISH TO MAKE ANY CORRECTIONS? ( 0 FOR NO ; VAR# FOR
YES )",I
3920 IF I=0 THEN Sidein3
3930 IF (I>0) AND (I<=P(1,4)) THEN GOSUB Sidein1
3940 IF (I>0) AND (I<=P(1,4)) THEN GOTO Sidein2
3950 GOSUB Err
3960 GOTO Sidein2

```

```

3970 ! -----
3980 Sidein1: ! ----- INPUT INITIAL DESIGN VARIABLES -----
3990 ! -----
4000 DISP "INPUT INITIAL X("&VAL$(I)&"),VLB,YUB : ( USE N FOR NO LOWER OR UPPE
R BOUND )";
4010 INPUT X(I),L$,U$
4020 IF L$="N" THEN VLB(I)=-1E50
4030 IF L$<>"N" THEN VLB(I)=VAL(L$)
4040 IF L$="N" THEN L$="NONE"
4050 IF U$="N" THEN VUB(I)=1E50
4060 IF U$<>"N" THEN VUB(I)=VAL(U$)
4070 IF U$="N" THEN U$="NONE"
4080 PRINT " X("&VAL$(I)&")="&X(I), " VLB="&L$, " VUB="&U$
4090 RETURN
4100 Sidein3: J=Ncon+1
4110 FOR I=1 TO P(1,4)
4120 IF VLB(I)<=-1E49 THEN Sidein4
4130 Wlincon(J)=-I
4140 J=J+1
4150 Addcon=Addcon+1
4160 Sidein4:NEXT I
4170 FOR I=1 TO P(1,4)
4180 IF VUB(I)>=1E49 THEN Sidein5
4190 Wlincon(J)=I
4200 J=J+1
4210 Addcon=Addcon+1
4220 Sidein5:NEXT I
4230 RETURN

```



```

4240 ! -----
4250 Sidein6: ! ----- INPUT CHECK FOR EXISTING PROGRAM -----
4260 ! -----
4270 PRINT PAGE
4280 PRINT TAB(10), "INPUT CHECK - INITIAL VALUES FOR THE DESIGN VARIABLES"
4290 PRINT LIN(2)
4300 Z=Ndv
4310 IF Z>15 THEN Z=15
4320 FOR I=1 TO Z
4330 L$=VAL$(V1b(I))
4340 IF V1b(I)=-1E50 THEN L$="NONE"
4350 U$=VAL$(Vub(I))
4360 IF Vub(I)=1E50 THEN U$="NONE"
4370 PRINT I: " X("&VAL$(I)&") = ";X(I), "V1b("&VAL$(I)&") = ";L$, "Vub("&VAL$(
I)&") = ";U$
4380 NEXT I
4390 DISP, "DO YOU WISH TO MAKE ANY CHANGES ( REF# OR 0 FOR NONE ) ";
4400 INPUT Ch
4410 IF Ch=0 THEN Sidein8
4420 IF (Ch>0) AND (Ch<=Z) THEN GOSUB Sidein7
4430 IF (Ch>0) AND (Ch<=Z) THEN Sidein6
4440 GOSUB Err
4450 GOTO Sidein6
! TRY AGAIN

```

```

4400 ! -----
4470 Sidein7: ! ----- ENTER CHANGE TO DESIGN VARIABLE -----
4480 ! -----
4490 DISP "INPUT CHANGE TO X("&VAL$(Ch)&"),VLB("&VAL$(Ch)&"),VUB("&VAL$(Ch)&")
";
4500 INPUT X(Ch),L$,U$
4510 IF L$="N" THEN VLB(Ch)=-1E50
4520 IF U$="N" THEN VUB(Ch)=1E50
4530 IF L$<>"N" THEN VLB(Ch)=VAL(L$)
4540 IF U$<>"N" THEN VUB(Ch)=VAL(U$)
4550 RETURN
4560 Sidein8: ! CONTINUE WITH INPUT CHECK
4570 IF Z<=15 THEN Sav
4580 Z=16
4590 PRINT PAGE
4600 PRINT TAB(10),"INPUT CHECK CONT. - INITIAL VALUES FOR THE DESIGN VARIA
ELES"
4610 PRINT LIN(2)
4620 FOR I=Z TO Ndv
4630 PPINT I;" X("&VAL$(I)&") = ";X(I),"VLB("&VAL$(I)&") = ";VLB(I),"VUB("&V
AL$(I)&") = ";VUB(I)
4640 NEXT I
4650 DISP "(DO YOU WISH TO MAKE ANY CHANGES ( PEF# OR 0 FOR NONE )";
4660 INPUT Ch
4670 IF Ch=0 THEN Sav
4680 IF (Ch>16) AND (Ch<=Ndv) THEN GOSUB Sidein7
4690 IF (Ch>16) AND (Ch<=Ndv) THEN GOTO 4650
4700 GOSUB Err
4710 GOTO 4650
4720 ! -----
4730 Err: ! ----- ERROR ROUTINE FOR ILLEGAL ENTRY -----
4740 ! -----
4750 PRINT PAGE
4760 BEEP
4770 PRINT LIN(10),TAB(10),"***** INPUT OUT OF RANGE - TRY AGAIN *****"
4780 WAIT 2000
4790 RETURN

```

```

4800 ! -----
4810 Err1: ! ----- ERROR ROUTINE FOR EXISTING PROGRAM -----
4820 ! -----
4830 PRINTER IS 16
4840 PRINT PAGE
4850 BEEP
4860 PRINT LTH(10),TAB(20),"***** ";Analyze$;" IS AN EXISTING PROGRAM *****"
4870 WAIT 5000
4880 OFF ERROR
4890 GOTO C10
4900 ! -----
4910 Err2: ! ----- ERROR ROUTINE FOR EXISTING DATA -----
4920 ! -----
4930 PRINT PAGE
4940 BEEP
4950 PRINT TAB(15),"*** READ ERROR ON EXISTING PROGRAM ***"
4960 PRINT LIN(2)
4970 PRINT "A READ ERROR HAS OCCURED WHILE ATTEMPTING TO READ EXISTING DATA."
4980 PRINT "THERE ARE SEVERAL POSSIBLE CAUSES FOR THIS TO HAVE HAPPENED."
4990 PRINT LIN(1)," 1. A MISTAKE WAS MADE WHILE INPUTING DATA. IF SO RES
TART"
5000 PRINT " THE PROGRAM BY PRESSING THE RUN KEY. "
5010 PRINT LIN(1)," 2. THE DATA FILES NO LONGER EXIST FOR ";Analyze$;" OP
HAVE AN EROR "
5020 PRINT " IN THEM. IF THIS IS THE CASE THEY MUST BE ERASED AND THE PR
OGRAM "
5030 PRINT " RESTRATED AS A NEW PROGRAM. PRESS THE CONT KEY TO ERASE THE
EXISTING"
5040 PRINT " DATA FILES FOR ";Analyze$;" AND RESTART THE PROBLEM."
5050 PAUSE
5060 PURGE P$
5070 PURGE D$
5080 OFF ERROR
5090 GOTO C10

```

```

5100 ! -----
5110 P20: ! ----- LAST CHANCE -----
5120 ! -----
5130 PPINTER IS 16
5140 PRINT PAGE
5150 PPINT TAB(10), "LAST CHANCE TO CHANGE YOUR MIND BEFORE OPTIMIZING"
5160 PPINT LIN(2), TAB(5), "1. RETURN TO THE CONTROL PARAMETER AND DESIGN VARIA
BLE INPUT ROUTINE."
5170 PRINT LIN(2), TAB(5), "2. PROCEED TO OPTIMIZE THE "; ANALIZ$; " FUNCTION."
5180 INPUT "INPUT YOUR DECISION : ", Ch
5190 IF Ch=1 THEN G9
5200 IF (Ch=2) AND (Prog2=1) THEN C1 ! OVERLAY THE DESOP PROGRAM
5210 IF (Ch<1) AND (Ch>2) THEN GOSUB Err
5220 GOTO P20
5230 ! -----
5240 Z99: ! ----- END -----
5250 ! -----
5260 END

```

APPENDIX E

DESOP Program Listing

In the development of the DESOP program, Refs. 2, 7, 8, 9, and 10 were used.

```

*****
*
*      DESOP
*
*      DESKTOP SEQUENTIAL UNCONSTRAINED MINIMIZATION
*      TECHNIQUE OPTIMIZATION PROGRAM
*
*      by W. B. COLE
*      NAVAL POSTGRADUATE SCHOOL, MONTEREY, CALIFORNIA
*      1980
*
*****
DATE OF LAST REVISION : 8/29/80
PROGRAM FEATURES :
1. SEARCH METHODS:
    A. STEEPEST DESCENT
    B. FLETCHER-REEVES
    C. BOTH OF WHICH ARE NORMALIZED
2. ALPHA BOUND - UTILIZES THE GOLDEN SECTION TECHNIQUE TO LOCATE THE
   FUNCTION MINIMUM. THE PREDICTED MINIMUM IS TESTED AGAINST THE
   ACTUAL VALUE OF OBJ AT THAT POINT.
3. A FOUR POINT CUBIC IS USED TO PREDICT THE MINIMUM.
4. IF THE CUBIC FIT FAILS THERE IS A QUADRATIC BACKUP.
5. ABOVEJ1 IS ADJUSTED ON EACH ITERATION.
6. THE DESIGN VARIABLES ARE NORMALIZED
*****
Opt1: ! CONTROL POINT FOR TRANSFER OF PROGRAM CONTROL FROM INPUT ROUTINE TO
! OPTIMIZER ROUTINE.

```

```

245 ! -----
250 ! -----
255 ! -----
260 Opt2: ! BEGIN
265 DIM X(30),G(30),Tmp(30),Params(50),Df(30),Vib(30),Vub(30),Dfo(30),S(30)
270 DIM Xsav(30),Gg(30),C(10),Xscal(30),Scal(30)
275 ! -----
280 ! READ CONTROL PARAMETERS AND INITIAL DESIGN VARIABLES
285 ! -----
290 DISP "READING CONTROL PARAMETERS AND DESIGN VARIABLES."
295 ASSIGN #1 TO P$
300 ASSIGN #2 TO D$
305 READ #1,1
310 READ #1:Ndv,Ncon,Iprint,Delfun,Dabfun,Itmax,Icendir,Fdch,Fdchm,Abobj1,Alpha
315 READ #1,3
320 READ #1;Irmax,Rz,Result,Exp9,Nscal
325 READ #2,1
330 FOR I=1 TO Ndv
335 READ #2;X(I)
340 NEXT I
345 READ #2,2
350 FOR I=1 TO Ndv
355 READ #2;Vib(I),Vub(I)
360 NEXT I
365 Niter=0
370 Ncal=0
375 Ncc=0
380 C(2)=Iprint
385 IF Iprint<0 THEN PRINTER IS 0
390 IF Iprint>0 THEN PRINTER IS 16
395 IF Ncon=0 THEN Irmax=1

```

! INITIALIZE PROGRAM PARAMETERS

```

400 FOR I=1 TO Ndv
405   Scal(I)=X(I)
410   IF Scal(I)<1 THEN Scal(I)=1
415   IF Nscal=0 THEN Scal(I)=1
420   Xscal(I)=X(I)/Scal(I)
425   Dfo(I)=0
430 NEXT I
435 ! -----
440 ! ----- INITIAL DESIGN -----
445 ! -----
450 DISP "EVALUATING THE OBJECTIVE AND CONSTRAINT FUNCTIONS AT X(0). "
455 ! FIRST AND LAST FLAG
460 C(1)=Icalc
465 CALL Analiz(X(*),G(*),Gg(*),C(*),Obj)
470 Ncal=Ncal+1
475 IF Ncon>0 THEN GOSUB Penalize
480 Icalc=2
485 Kcalc=0
490 C(1)=Icalc
495 !
500 Objav=Obj
505 PRINTER IS 0
510 IF Iprint=6 THEN PRINTER IS 16
515 IF Iprint=6 THEN PRINT PAGE
520 IF Iprint=6 THEN GOTO 540
525 PRINT LIN(2)
530 PRINT "
-----"
535 PRINT LIN(3)
540 PRINT "
545 PRINT LIN(2), "DESIGN VARIABLES : "
550 FOR I=1 TO Ndv
555 PRINT "X("VAL$(I)&"")=";X(I),
560 NEXT I
565 IF Ncon<=0 THEN GOTO 590

```



```

570 PRINT LIN(2), "CONSTRAINTS : "
575 FOR I=1 TO Ncon
580 PRINT "G(" & VAL$(I) & ")=" & G(I),
585 NEXT I
590 PRINT LIN(2), "OBJECTIVE FUNCTION : "
595 PRINT "OBJ=" & OBJ, "OBJA " & OBJa
600 IF Iprint > 0 THEN PRINTER IS 16
605 DISP "PRESS 'CONT' TO CONTINUE"
610 DISP "OPTIMIZER RUNNING"
615 OI: CONTINUE
620 ! -----
625 ! ----- OUTER LOOP FOR PENALTY FUNCTION -----
630 ! -----
635 FOR Itr=1 TO Irmx
640 Objsov=Obj
645 Kount=0
650 Dfold2=1
655 ! -----
660 ! ----- INNER LOOP, NO INCREASE IN PENALTY FUNCTION -----
665 ! -----
670 FOR Itm=1 TO Itmx
675 Niter=Niter+1
680 Kount=Kount+1
685 IF Kscal < 0 THEN GOTO 720
690 FOR I=1 TO Hdv
695 Scal(I)=Xscal(I)*Scal(I)
700 IF Scal(I) < 1 THEN Scal(I)=1
705 IF Nscal=0 THEN Scal(I)=1
710 Xscal(I)=X(I)/Scal(I)
715 NEXT I
720 Kscal=Kscal+1
725 IF Kscal=Ndv+2 THEN Kscal=0
730 IF Iprint < 0 THEN PRINTER IS 0
735 IF ABS(Iprint) > 1 THEN PRINT LIN(2)
740 IF ABS(Iprint) > 1 THEN PRINT "*****"
*****
! SCALE THE DESIGN VARIABLES

```

```

745 IF ABS(Iprint)>1 THEN PRINT LIN(1),"ITERATION NUMBER : ";Niter
750 ! -----
755 ! ----- EVALUATE THE GRADIENT OF THE OBJECTIVE FUNCTION AND ANY
760 ! ----- ACTIVE CONSTRAINTS AT X(0) -----
765 ! -----
770 DISP "CALCULATING THE GRADIENTS"
775 GOSUB Grad
780 !
785 IF ABS(Iprint)>3 THEN PRINT "GRADIENTS : "
790 FOR I=1 TO Ndu
795 IF ABS(Iprint)>3 THEN PRINT " DF("ZVAL$(I)&">";Df(I),
800 NEXT I
805 DISP "FINDING THE SEARCH DIRECTION"
810 ! -----
815 05: ! ----- FIND THE SEARCH DIRECTION -----
820 ! -----
825 Df2=0
830 Dfold2=0
835 FOR I=1 TO Ndu
840 Dfold2=Dfold2+Dfo(I)^2
845 Df2=Df2+Df(I)^2
850 NEXT I
855 IF Kount>1 THEN 02 ! USE FLETCHER REEVES
860 ! -----
865 ! ----- CALCULATION OF THE SEARCH DIRECTION BY STEEPEST DESCENT -----
870 ! -----
875 Fact=1E-3
880 FOR I=1 TO Ndu
885 S(I)=-Df(I) ! SEARCH DIRECTION
890 IF ABS(S(I))>Fact THEN Fact=ABS(S(I)) ! NORMALIZE SEARCH DIRECTION
895 Dfo(I)=Df(I)
900 NEXT I
905 FOR I=1 TO Ndu
910 S(I)=S(I)/Fact
915 NEXT I
920 IF ABS(Iprint)>2 THEN PRINT LIN(1),"SEARCH METHOD : STEEPEST DESCENT"
925 GOTO 03 ! BRANCH AROUND FLETCHER REEVES

```

```

930 02: ! CONTINUE
935 ! -----
940 ! -----CALCULATION OF SEARCH DIRECTION BY FLETCHER REEVES-----
945 ! -----
950 Beta=Df2*Fact/Dfold2
955 Fact=1E-3
960 FOR I=1 TO Ndv
965 S(I)=-Df(I)+Beta*S(I)
970 IF ABS(S(I))>Fact THEN Fact=ABS(S(I))
975 Dfo(I)=Df(I)
980 NEXT I
985 FOR I=1 TO Ndv
990 S(I)=S(I)/Fact
995 NEXT I
1000 IF ABS(Iprint)>2 THEN PRINT LIN(1), "SEARCH METHOD : FLETCHER REEVES"
1005 03: ! CONTINUE
1010 IF Kount=Icndir THEN Kount=0
1015 FOR I=1 TO Ndv
1020 IF ABS(Iprint)>2 THEN PRINT " S("&VAL$(I)&" )=";S(I),
1025 NEXT I
1030 ! -----
1035 ! -----CALCULATE THE SLOPE OF THE OBJECTIVE FUNCTION AT X(0) WITH-----
1040 ! -----RESPECT TO ALPHA -----
1045 ! -----
1050 Dfdalp=0
1055 FOR I=1 TO Ndv
1060 Dfdalp=Dfdalp+Df(I)*S(I)
1065 NEXT I
1070 IF ABS(Dfdalp)<1E-20 THEN GOTO 099
1075 IF ABS(Iprint)>2 THEN PRINT LIN(1), "DFDALP = ";Dfdalp
1080 IF Dfdalp=0 THEN Kount=0
1085 IF Dfdalp>0 THEN PRINT "THE OBJECTIVE FUNCTION HAS A POSITIVE SLOPE."
1090 IF Dfdalp>0 THEN PRINT "RESTART THE SEARCH USING STEEPEST DESCENT."
1095 IF Dfdalp>0 THEN 05
! START OVER WITH STEEPEST DESCENT

```

```

1100 ! -----
1105 ! ----- ESTIMATE ALPHA IN THE 1-D SEARCH -----
1110 ! -----
1115 DISP "CALCULATING AN INITIAL ALPHA"
1120 !
1125 GOSUB Alpges
1126 IF Alp3<1E-12 THEN Alp3=1E-12
1130 IF ABS(Iprint)>2 THEN PRINT "ALPHA GUESS =";Alp3
1135 IF Iprint=6 THEN DISP "PRESS 'CONT' TO CONTINUE."
1140 IF Iprint=6 THEN PAUSE
1145 04: ! CONTINUE
1150 ! -----
1155 ! ----- CALCULATE ALPHA IN THE 1-D SEARCH -----
1160 ! -----
1165 !
1170 DISP "FINDING ALPHA "
1175 !
1180 GOSUB Alpbnd
1185 !
1190 ! -----
1195 ! ----- ITERATION RESULTS -----
1200 ! -----
1205 PRINT LIN(1),"RESULTS : "
1210 FOR I=1 TO Ndu
1215 X(I)=Xscal(I)+Scal(I)
1220 PRINT "X("&VAL$(I)&")=";X(I),
1225 NEXT I
1230 IF Ncon=0 THEN GOTO 1255
1235 PRINT LIN(1)
1240 FOR I=1 TO Ncon
1245 PRINT "G("&VAL$(I)&")=";G(I),
1250 NEXT I
1255 PRINT LIN(1),"OBJ = ";Obj;"OBJA = ";ObjA
1260 DISP "PRESS 'CONT' TO CONTINUE"

```

```

1265 ! -----
1270 ! ----- CHECK FOR CONVERGENCE -----
1275 ! -----
1280 !
1285 GOSUB Converg
1290 !
1295 IF ABS(Iprint)>2 THEN PRINT "DEL=";Del,"CONI=";Coni,LIN(1),"ABOBI=";Abobi
1300 !
1305 IF Iprint=6 THEN PAUSE
1310 IF Coni>=2 THEN DISP "CONVERGENCE MET, INCREASE THE PENALTY FUNCTION."
1315 IF Coni>=2 THEN GOTO 1335 ! IF CONVERGENCE IS SATISFIED TWICE
1320 ! PROCEED TO INCREMENT RZ
1325 ! -----
1330 ! NEXT Itr
1335 ! -----
1340 RZ=RZ*Rmult ! INCREASE THE PENALTY FUNCTION
1345 RZ=RZ+1 ! COUNTER ON PENALTY INCREASES
1350 IF ABS(Iprint)>=2 THEN PRINT "RZ HAS BEEN INCREASED ";RZ;" TIMES TO ";RZ
1355 FOR I=1 TO Hdu
1360 X(I)=Xscal(I)*Scal(I)
1365 NEXT I
1370 CALL Analiz(X(*),G(*),Gg(*),C(*),Obj)
1375 Ncal=Ncal+1
1380 IF Ncon>0 THEN GOSUB Penalize
1385 GOSUB Converg
1390 IF Coni=3 THEN GOTO 099
1395 Coni=0
1400 ! -----
1405 ! NEXT Itr
1410 ! -----
1415 ! -----
1420 099: ! ----- OPTIMIZATION RESULTS -----
1425 ! -----
1430 IF Iprint=6 THEN GOTO 1455
1435 PRINTER IS 0
1440 PRINT LIN(2)

```

```

1445 PRINT "-----"
1450 PRINT LIN(2)
1455 IF Iprint=6 THEN PRINT PAGE
1460 PRINT "
1465 PRINT LIN(3), "FINAL DESIGN VARIABLES : "
1470 FOR I=1 TO HdV
1475 X(I)=Xscal(I)*Scal(I)
1480 PRINT "%(" & VAL$(I) & ") = "; X(I),
1485 NEXT I
1490 IF Hcon<=0 THEN G6
1495 PRINT LIN(2), "FINAL CONSTRAINTS : "
1500 FOR I=1 TO Hcon
1505 PRINT "G(" & VAL$(I) & ")="; G(I),
1510 NEXT I
1515 G6: PRINT LIN(2), "FINAL OBJECTIVE FUNCTION : "
1520 PRINT "OBJ="; Obj, "OBJA="; ObjA
1525 PRINT LIN(2), "NUMBER OF ITERATIONS :"; Niter
1530 PRINT LIN(2), "NUMBER OF TIMES ANALYZE CALLED :"; Hcal
1535 PRINT LIN(2), "RZ HAS BEEN INCREASED "; RZ; " TIMES TO "; Rz
1540 I PRINT ANY RESULTS SPECIFIED BY ANALYZE
1545 Icalc=3
1550 C(I)=Icalc
1555 CALL Analyz(X(*), G(*), Gg(*), C(*), Obj)
1560 DISP "END OF PROGRAM."
1565 LOAD "OPCON", C8
1570 END

```

```

1575 ! *****
1580 Grad: ! ----- SUBROUTINE GRAD -----
1585 ! *****
1590 ! *****
1595 ! -----
1600 ! -----STORE THE CURRENT VALUES OF THE ANALIZE SUBROUTINE -----
1605 ! -----
1610 Obj$av=Obj
1615 IF Ncon<=0 THEN GOTO G1
1620 FOR J=1 TO Ncon
1625 Tmp(J)=G(J)
1630 NEXT J
1635 G1: ! CONTINUE
1640 ! -----
1645 ! ----- CALCULATE THE GRADIENTS -----
1650 ! -----
1655 FOR J=1 TO Ndv
1660 Xsav=Xscal(J)
1665 Dx=ABS(Xsav)*Fdch
1670 IF Dx<Fdchm THEN Dx=Fdchm
1675 Xscal(J)=Xscal(J)+Dx
1680 ! -----
1685 ! ----- CALCULATE THE FUNCTION AT X(J) + Dx(J) -----
1690 ! -----
1695 X(J)=Xscal(J)*Scal(J)
1700 CALL Analiz(X(*),G(*),Gg(*),C(*),Obj) ! CONVERT TO REAL X(*) TO ANALIZE
1705 Ncal=Ncal+1
1710 IF Ncon>0 THEN GOSUB Penalize
1715 !
1720 Df(J)=(Obj-Obj$av)/Dx

```

```

1725 ! ----- RETURN X(I) AND OBJ TO THEIR ORIGINAL VALUES -----
1730 !
1735 !
1740 Xscal(J)=Xsav
1745 X(J)=Xscal(J)*Scal(J)
1750 NEXT J
1755 Obj=Objsav
1760 IF Ncon<=0 THEN GOTO G2
1765 FOR J=1 TO Ncon
1770 G(J)=Tmp(J)
1775 NEXT J
1780 G2: ! CONTINUE
1785 RETURN
1790 !

```



```

1795 ! *****
1800 Alpges: ! ----- SUBROUTINE ALPGES -----
1805 ! *****
1810 ! *****
1815 ! -----
1820 ! CALCULATE AN INITIAL ESTIMATE FOR ALPHA IN THE 1-D SEARCH
1825 ! -----
1830 Denom=ABS(Dfdalp)
1835 Anum=ABS(OBJ)
1840 IF Denom<1E-5 THEN Denom=1E-5
1845 IF Anum<1 THEN Anum=1
1850 Alp3=Abobj1*Anum/Denom
1855 FOR I=1 TO Ndu
1860 Axi=ABS(Xscal(I))
1865 IF Axi<1 THEN Axi=1
1870 Asi=ABS(S(I))
1875 IF Asi<1E-5 THEN Asi=1E-5
1880 Alp=Alphax*Axi*Asi
1885 IF Alp<Alp3 THEN Alp3=Alp
1890 NEXT I

```

! PROTECT AGAINST DIVISION BY 0
! PROTECT AGAINST A SMALL NUMERATOR
! ALP3 = PRESENT UPPER BOUND

```

1895 ! ----- CHECK TO SEE IF ANY SIDE CONSTRAINTS ARE VIOLATED -----
1900 ! -----
1905 ! -----
1910 FOR I=1 TO NdV
1915 V1scal(I)=V1b(I)/Scal(I)
1920 Vuscal(I)=Vub(I)/Scal(I)
1925 IF ABS(Xscal(I)-V1scal(I))>1E50 THEN Ag1
1930 IF ABS(S(I))<1E-20 THEN Ag1
1935 Alp=(Xscal(I)-V1scal(I))/S(I)
1940 IF ABS(Alp)<ABS(Alp3) THEN Alp3=Alp
1945 Ag1: !
1950 IF ABS(Xscal(I)-Vuscal(I))>1E50 THEN Ag2
1955 IF ABS(S(I)) THEN Ag2
1960 Alp=(Vuscal(I)-Xscal(I))/S(I)
1965 IF ABS(Alp)<ABS(Alp3) THEN Alp3=Alp
1970 Ag2: !
1975 Alp3=ABS(Alp3)
1980 NEXT I
1985 !
1990 RETURN
1995 !

```

```

2000 ! *****
2005 Alpbnd: ! ----- SUBROUTINE ALPBND -----
2010 ! *****
2015 ! *****
2020 ! -----
2025 ! ----- FIND ALPHA -----
2030 ! -----
2035 ! -----
2040 IF ABS(Iprint)>4 THEN PRINT "SUBROUTINE : ALPBND"
2045 IF ABS(Iprint)=5 THEN PRINT "DETERMINING THE UPPER AND LOWER BOUNDS ON AL
PHA."
2050 ! -----
2055 ! ----- SAVE INPUT PARAMETERS -----
2060 ! -----
2065 Obj sav=Obj
2070 FOR I=1 TO Ndu
2075 Xsav(I)=Xscal(I)
2080 NEXT I
2085 IF Ncon<=0 THEN GOTO A1
2090 FOR I=1 TO Ncon
2095 Tmp(I)=G(I)
2100 NEXT I
2105 A1: ! CONTINUE
2110 ! -----
2115 ! ----- INITIAL BOUNDS -----
2120 ! -----
2125 Alpz=0
2130 Fz=Obj
2135 A6: ! TRANSFER
2140 FOR I=1 TO Ndu
2145 Xscal(I)=Xsav(I)+Alp3*S(I)
2150 X(I)=Xscal(I)*Scal(I)
2155 NEXT I
2160 !
2165 CALL Analiz(X(*),G(*),Gg(*),C(*),Obj)
2170 Ncal=Ncal+1
2175 IF Ncon>0 THEN GOSUB Penalize
2180 F3=Obj

```

```

2185 IF ABS(Iprint)>4 THEN PRINT "INITIAL BOUNDS."
2190 IF ABS(Iprint)>4 THEN PRINT "ALPHA2=";Alp2,"F2=";F2
2195 IF ABS(Iprint)>4 THEN PRINT "ALPHA3=";Alp3,"F3=";F3
2200 !
2205 ! IF F3 IS GREATER THEN F2 THE MIN. EXISTS BETWEEN ALP2 AND ALP3
2210 IF F3>F2 THEN GOTO A3
2215 ! ----- INCREASE THE BOUNDS ON ALPHA -----
2220 A2: !
2225 !
2230 D1=Alp3-Alp2
2235 Alp1=Alp3
2240 F1=F3
2245 Alp3=Alp2+D1/.3819650113
2250 FOR I=1 TO Ndu
2255 Xscal(I)=Xsav(I)+Alp3*S(I)
2260 X(I)=Xscal(I)*Scal(I)
2265 NEXT I
2270 !
2275 CALL Analiz(X(*),G(*),Gg(*),C(*),Obj)
2280 Ncal=Ncal+1
2285 IF Ncon>0 THEN GOSUB Penalize
2290 F3=Obj
2295 IF ABS(Iprint)>4 THEN PRINT "INCREASE THE BOUNDS ON ALPHA"
2300 IF ABS(Iprint)>4 THEN PRINT "ALPHA2=";Alp2,"F2=";F2
2305 IF ABS(Iprint)>4 THEN PRINT "ALPHA1=";Alp1,"F1=";F1
2310 IF ABS(Iprint)>4 THEN PRINT "ALPHA3=";Alp3,"F3=";F3
2315 !
2320 ! IF OBJ IS GREATER THAN F1
2325 ! THE MINIMUM EXISTS BETWEEN ALP2 AND ALP3.
2330 ! PROCEED TO LOCALIZE THE MINIMUM.
2335 ! OTHERWISE INCREASE THE UPPER AND LOWER BOUNDS
2340 ! AND PROCEED TO SEARCH FOR THE MINIMUM.
2345 ! -----
2350 IF F3>F1 THEN GOTO A4
2355 F2=F1
2360 Alp2=Alp1
2365 GOTO A2
2370 !

```

! INCREMENT X(I) BY ALP3

```

2375 A3: ! CALCULATE ALPHA1 AND F1
2380 D1=Alp3-Alpz
2385 Alp1=Alpz+D1*.3819660113
2390 FOR I=1 TO Ndu
2395 Xscal(I)=Xsav(I)+Alp1*S(I)
2400 X(I)=Xscal(I)*Scal(I)
2405 NEXT I
2410 CALL Analiz(X(*),G(*),Gg(*),C(*),Obj)
2415 Ncal=Ncal+1
2420 IF Ncon>0 THEN GOSUB Penalize
2425 F1=Obj
2430 IF F1>F2 THEN Alp3=Alp1
2435 IF F1>F2 THEN GOTO A6
2440 !
2445 A4: ! CONTINUE
2450 !
2455 ! ----- THE MINIMUM IS BRACKETED -----
2460 !
2465 IF ABS(Iprint)>5 THEN PRINT "THE MINIMUM IS BRACKETED - PROCEED TO LOCALI
ZE IT."
2470 D1=Alp3-Alpz
2475 Alp2=Alpz+.6180339887*D1
2480 ! CALCULATE F2
2485 FOR I=1 TO Ndu
2490 Xscal(I)=Xsav(I)+Alp2*S(I)
2495 X(I)=Xscal(I)*Scal(I)
2500 NEXT I
2505 CALL Analiz(X(*),G(*),Gg(*),C(*),Obj)
2510 IF Ncon>0 THEN GOSUB Penalize
2515 Ncal=Ncal+1
2520 F2=Obj
2525 A5: ! TEST FOR LOCALIZATION.
2530 IF ABS(Iprint)>4 THEN PRINT "LOCALIZE THE MINIMUM"
2535 IF ABS(Iprint)>4 THEN PRINT "ALPHA2=";Alpz,"F2=";F2
2540 IF ABS(Iprint)>4 THEN PRINT "ALPHA1=";Alp1,"F1=";F1
2545 IF ABS(Iprint)>4 THEN PRINT "ALPHA2=";Alp2,"F2=";F2
2550 IF ABS(Iprint)>4 THEN PRINT "ALPHA3=";Alp3,"F3=";F3

```

```

2555 ! ----- TEST THE VERTICAL DIFFERENCE ON THE FOUR F's -----
2560 ! -----
2565 ! -----
2570 IF (ABS((Fz-F1)/F1)>.1) OR (ABS((Fz-F2)/F2)>.1) THEN GOTO A11
2575 IF (ABS((F3-F1)/F1)>.1) OR (ABS((F3-F2)/F2)>.1) THEN GOTO A11
2580 ! -----
2585 ! TEST TO SEE IF THE CUBIC INTERPOLATOR WILL GIVE A GOOD
2590 ! APPROXIMATION FOR THE MINIMUM ALPHA.
2595 ! -----
2600 GOSUB Quebec
2605 Objq=A0+A1*Alpha+A2*Alpha^2+A3*Alpha^3
2610 ! CALCULATE OBJ AT THE ALPHA GIVEN
2615 FOR I=1 TO Nd
2620 Xscal(I)=X330(I)+Alpha*S(I)
2625 X(I)=Xscal(I)*Scal(I)
2630 NEXT I
2635 CALL Analyz(X(*),G(*),Gg(*),C(*),Obj)
2640 IF Ncon>0 THEN GOSUB Penalize
2645 Ncal=Ncal+1
2650 A10: ! TEST THE TWO RESULTS FOR AGREEMENT
2655 IF ABS(Iprint)>2 THEN PRINT "OBJ=";Obj;"          OBJQ=";Objq
2660 IF ABS((Objq-Obj)/Obj)>1E-3 THEN GOTO A7
2665 IF D1<1E-3 THEN GOTO A7
2670 ! -----
2675 A11: ! ----- PROCEED WITH THE GOLDEN SEARCH FOR THE MINIMUM -----
2680 ! -----
2685 IF D1<1E-12 THEN GOTO A7          ! EVEN THOUGH MIN NOT FOUND - EXIT
2690 IF F1>F2 THEN GOTO A12
2695 IF ABS(Iprint)=5 THEN PRINT "F1<F2"
2700 Alp3=Alp2
2705 F3=F2
2710 Alp2=Alp1
2715 F2=F1
2720 D1=Alp3-Alp2
2725 Alp1=Alp2+.3819660113*D1

```

```

2730 ! CALCULATE F1
2735 FOR I=1 TO Ndv
2740 Xscal(I)=Xsav(I)+Alp1*S(I)
2745 X(I)=Xscal(I)+Scal(I)
2750 NEXT I
2755 CALL Analiz(X(*),G(*),Gg(*),C(*),Obj)
2760 IF Ncon>0 THEN GOSUB Penalize
2765 Hcal=Hcal+1
2770 F1=Obj
2775 GOTO A5
2780 !
2785 A12: ! CONTINUE
2790 IF ABS(Iprint)=5 THEN PRINT "F1 >= F2"
2795 Alp2=Alp1
2800 Fz=F1
2805 Alp1=Alp2
2810 F1=F2
2815 D1=Alp3-Alp2
2820 Alp2=Alp2+.6180339887*D1
2825 ! CALCULATE F2
2830 FOR I=1 TO Ndv
2835 Xscal(I)=Xsav(I)+Alp2*S(I)
2840 X(I)=Xscal(I)+Scal(I)
2845 NEXT I
2850 CALL Analiz(X(*),G(*),Gg(*),C(*),Obj)
2855 IF Ncon>0 THEN GOSUB Penalize
2860 Hcal=Hcal+1
2865 F2=Obj
2870 GOTO A5
2875 !
2880 A7: ! CONTINUE
2885 !
2890 RETURN
2895 !
2900 !

```

```

2905 ! *****
2910 Queoic: ! ----- SUBROUTINE QUEBIC -----
2915 ! *****
2920 !
2925 !
2930 !
2935 ! ROUTINE TO ESTIMATE THE ALPHA AT WHICH OBJ IS A MINIMUM BASED
2940 ! ON FOUR POINT CUBIC INTERPOLATION.
2945 !
2950 IF ABS(Iprint)<5 THEN GOTO 2975
2955 PRINT "CUBIC INTERPOLATOR INPUT"
2960 PRINT "ALPHA2="; Alp2, "F2="; F2
2965 PRINT "ALPHA1="; Alp1, "F1="; F1
2970 PRINT "ALPHA2="; Alp2, "F2="; F2
2975 PRINT "ALPHA3="; Alp3, "F3="; F3
2980 Q1=Alp2^3*(Alp2-Alp1)-Alp1^3*(Alp2-Alp2)+Alp2^3*(Alp1-Alp2)
2985 Q2=Alp2^3*(Alp3-Alp1)-Alp1^3*(Alp3-Alp2)+Alp3^3*(Alp1-Alp2)
2990 Q3=(Alp2-Alp1)*(Alp1-Alp2)*(Alp2-Alp2)
2995 Q4=(Alp3-Alp1)*(Alp1-Alp2)*(Alp3-Alp2)
3000 Denq=Q2+Q3-Q1*Q4
3005 Q5=F2*(Alp1-Alp2)-F1*(Alp2-Alp2)+F2*(Alp2-Alp1)
3010 Q6=F3*(Alp1-Alp2)-F1*(Alp3-Alp2)+F2*(Alp3-Alp1)
3015 A3=(Q3+Q6-Q4*Q5)/Denq
3020 A2=(Q5-Q1*A3)/Q3
3025 A1=(F1-F2-A3*(Alp1^3-Alp2^3))/(Alp1-Alp2)-A2*(Alp2+Alp1)
3030 A0=F2-A1*Alp2-A2*Alp2^2-A3*Alp2^3
3035 IF A3=0 THEN GOTO Q10
3040 !
3045 ! THE GENERAL EQUATIONS OF THE FUNCTION ARE THEN
3050 !  $Y = A0 + A1*X + A2*X^2 + A3*X^3$ 
3055 !  $dY/dX = A1 + 2*A2*X + 3*A3*X^2$ 
3060 !  $d2Y/dX2 = 2*A2 + 6*A3*X$ 
3065 ! FIND THE MINIMUM USING FIRST AND SECOND DERIVATIVES.

```



```

3070 ON ERROR GOTO 3080
3075 X1=(-A2+(A2^2-3*A1*A3)^.5)/(3*A3)
3080 OFF ERROR
3085 ON ERROR GOTO 3095
3090 X2=(-A2-(A2^2-3*A1*A3)^.5)/(3*A3)
3095 OFF ERROR
3100 Y2p=2*A2+6*A3*X1
3105 IF Y2p>0 THEN Alpha=Xx1
3110 IF Y2p<0 THEN Alpha=Xx2
3115 IF (Alpha>Alpz) AND (Alpha<Alp3) THEN GOTO Q1
3120 ! ----- THE PREDICTED MINIMUM IS OUTSIDE THE BRACKETED MINIMUM -----
3125 !
3130 !
3135 IF F1>F2 THEN GOTO Q2
3140 ! F1<F2 : FIND THE MINIMUM USING A QUADRATIC FIT
3145 W1=(Alp1-Alpz)*(F2-Fz)-(Alp2-Alpz)*(F1-Fz)
3150 W2=(Alp1-Alpz)*(Alp2-Alpz)*(Alp2-Alp1)
3155 W3=W1/W2
3160 W4=(F1-Fz)/(Alp1-Alpz)-(Alpz+Alp1)*W3
3165 Alpha=-W4/(2*W3)
3170 GOTO Q3
3175 Q2: ! F1 > F2 : FIND THE MINIMUM USING A QUADRATIC FIT
3180 W1=(Alp2-Alp1)*(F3-F1)-(Alp3-Alp1)*(F2-F1)
3185 W2=(Alp2-Alp1)*(Alp3-Alp1)*(Alp3-Alp2)
3190 W3=W1/W2
3195 W4=(F2-F1)/(Alp2-Alp1)-(Alp1+Alp2)*W3
3200 Alpha=-W4/(2*W3)
3205 GOTO Q3

```

```

3210 Q1: IF ABS(IPRINT)<5 THEN GOTO 3260
3215 PRINT "CUBIC OUTPUT"
3220 PRINT "Q1=";Q1,"Q2=";Q2
3225 PRINT "Q3=";Q3,"Q4=";Q4
3230 PRINT "Q5=";Q5,"Q6=";Q6
3235 PRINT "A0=";A0,"A1=";A1
3240 PRINT "A2=";A2,"A3=";A3
3245 PRINT "X1=";X1,"X2=";X2
3250 PRINT "Y2P=";Y2P
3255 Q3: IF ABS(IPRINT)>2 THEN PRINT "ALPHA=";Alpha
3260 RETURN
3265 Q10: ! IF A3=0 THEN THE FUNCTION IS A QUADRATIC
3270 Alpha=-A1/(2*A2)
3275 IF ABS(IPRINT)<5 THEN GOTO 3295
3280 PRINT "THE FUNCTION IS A QUADRATIC"
3285 PRINT "A1=";A1,"A2=";A2
3290 PRINT "ALPHA=";Alpha
3295 RETURN
3300 !

```

```

3305 ! *****
3310 Convg: ! ----- SUBROUTINE CONVRG -----
3315 ! *****
3320 ! *****
3325 ! -----
3330 ! ----- CHECK ON CONVERGENCE CRITERIA -----
3335 ! -----
3340 ! -----
3345 Del=ABS((Obj-Objsav)/Obj)
3350 Abobj1=(Abobj1+Del)/2
3355 IF Del<Delfun THEN Coni=Coni+1 ! INCREASE CONVERGENCE COUNTER BY 1
3360 IF Del<Delfun THEN Kount=0 ! NEXT ITERATION - STEEPEST DECENT
3365 IF Del<Delfun THEN RETURN
3370 IF ABS(Obj-Objsav)<Dabfun THEN Coni=Coni+1
3375 IF ABS(Obj-Objsav)<Dabfun THEN Kount=0
3380 Obj sav=Obj
3385 RETURN
3390 !
3395 !

```

```

3400 ! *****
3405 Penalize: ! ----- SUBROUTINE PENALIZE -----
3410 ! *****
*
3415   ObjA=Obj
3420 ! -----
3425 ! ----- ADD PENALTIES FOR VIOLATED CONSTRAINTS. -----
3430 ! -----
3435   FOR I=1 TO Ncon
3440     G1=G(I)
3445     IF G1>0 THEN Obj=Obj+Rz+G1^Exp9
3450     NEXT I
3455 ! -----
3460 Penal1: ! ----- ADD PENALTIES FOR VIOLATED SIDE CONSTRAINTS. -----
3465 ! -----
3470   FOR I=1 TO Ndu
3475     X(I)=Xscal(I)*Scal(I)
3480     IF X(I)<Vlb(I) THEN Obj=Obj+Rz*(X(I)-Vlb(I))/X(I)^Exp9
3485     IF X(I)>Vub(I) THEN Obj=Obj+Rz*(X(I)-Vub(I))/Vub(I)^Exp9
3490     NEXT I
3495   RETURN
3500 ! -----
3505 ! -----
3510 ! -----
3515 ! -----
3520 ! -----
3525 Analyz1: ! ATTACHMENT POINT FOR ANALYZE ROUTINE.
3530 ! -----
3535   END

```

APPENDIX F DESOP Test Programs

```

100 SUB Analiz(X(*),G(*),Gg(*),C(*),Obj)
110 !
120 !
130 !
140 ! A TEST PROGRAM FOR OPTIMIZER DEVELOPEMENT
150 ! THERE ARE NO CONSTRAINTS ON THE BANANA FUNCTION.
160 ! THERE ARE NO SIDE CONSTRAINTS ON THE BANANA FUNCTION.
170 ! NDV = 2
180 ! NCON = 0
190 ! RECOMMENDED STARTING VALUES ARE:
200 ! X(1) = -1.2
210 ! X(2) = 1.0
220 ! TRUE MINIMUM = 4.00
230 !
240 !
250 !
260 ! DESIGN VARIABLES :
270 X1=X(1)
280 X2=X(2)
290 ! OBJECTIVE FUNCTION :
300 Obj=10*(X2-X1^2)^2+(1-X1)^2+4
310 SUBEND

```

```

100 SUB Analyz(X(*),G(*),Gg(*),C(*),Obj)
110 !
120 ! ----- ROSEN-SUZUKI FUNCTION
130 ! A CONSTRAINED OPTIMIZATION PROBLEM
140 !
150 ! A TEST PROGRAM FOR OPTIMIZER DEVELOPMENT
160 ! THERE ARE NO SIDE CONSTRAINTS ON THE ROSEN-SUZUKI FUNCTION.
170 ! NDV = 4
180 ! NCON = 3
190 ! RECOMMENDED STARTING VALUES:
200 ! ALL X(I) = 1
210 ! TRUE MINIMUM = 6.00
220 !
230 ! -----
240 !
250 ! DESIGN VARIABLES :
260 X1=X(1)
270 X2=X(2)
280 X3=X(3)
290 X4=X(4)
300 ! OBJECTIVE FUNCTION :
310 Obj=X1^2-5*X1+X2^2-5*X2+2*X3^2-21*X3+X4^2+7*X4+50
320 ! CONSTRAINTS
330 G(1)=X1^2+X1+X2^2-X2+X3^2+X3+X4^2-X4-8
340 G(2)=X1^2-X1+2*X2^2+2*X3^2+2*X4^2-X4-10
350 G(3)=2*X1^2+2*X1+X2^2-X2+X3^2-X4-5
360 !
370 SUBEND

```

```

100 SUB Analiz(X(*),G(*),Gg(*),C(*),Obj)
110 GOTO 490
120 !
130 !
140 !
150 !
160 !
170 !
180 !
190 !
200 !
210 !
220 !
230 !
240 !
250 !
260 !
270 !
280 !
290 !
300 !
310 !
320 !
330 !
340 !
350 !
360 !
370 !
380 !
390 !
400 !
410 !
420 !
430 !
440 !
450 !

      "TSVAR"

      A CONSTRAINED OPTIMIZATION PROBLEM

      Himmelblau, D. M., Applied Nonlinear Programming, McGraw Hill Book
      Co., San Francisco, 1972, pp.410-412

      CODED BY : Walter B. Cole, June 9, 1980

      NDV = 5
      NCON = 6
      THERE ARE 10 SIDE CONSTRAINTS
      - RECOMMENDED STARTING VALUES ARE :
        X(1) = 2.52
        X(2) = 2
        X(3) = 37.5
        X(4) = 9.25
        X(5) = 6.8

      SIDE CONSTRAINTS TO BE ENTERED ON INPUT
        1. 0 <= X1 <= 5
        2. 1.2 <= X2 <= 2.4
        3. 20 <= X3 <= 60
        4. 9 <= X4 <= 9.3
        5. 6.5 <= X5 <= 7

      FINAL RESULTS :
      OBJ = -5280254
      X(1) = 4.538
      X(2) = 2.400
      X(3) = 60.000
      X(4) = 9.300
      X(5) = 7.000

```

```

460 ! -----
470 !
480 ! DESIGN VARIABLES :
490 X1=X(1)
500 X2=X(2)
510 X3=X(3)
520 X4=X(4)
530 X5=X(5)
540 !
550 ! CONSTANTS :
560 P1=-145421.402
570 K2=2931.1506
580 K3=-40.427932
590 K4=5106.192
600 K5=15711.36
610 K6=-161622.577
620 K7=4176.15328
630 K8=2.8260078
640 K9=9200.476
650 K10=13160.295
660 K11=-21686.9194
670 K12=123.56928
680 K13=-21.118894
690 K14=706.834
700 K15=2898.573
710 K16=28298.388
720 K17=60.81096
730 K18=31.242116
740 K19=329.574
750 K20=-2882.082
760 K21=74095.3845
770 K22=-306.262544
780 K23=16.243649
790 K24=-3094.252
800 K25=-5566.2628
810 K26=-26237
820 K27=99

```



```

830 K28=-.42
840 K29=1300
850 K30=2100
860 K31=925548.252
870 K32=-61968.8432
880 K33=23.3088196
890 K34=-27097.648
900 K35=-50843.766
910 !
920 X6=(K1+K2+K3+K4+K5+K6)*X1
930 Y1=K6+K1+K2+K3+K4+K5+K6
940 Y2=K11+K12+K13+K14+K15+K16
950 Y3=K16+K17+K18+K19+K20+K21
960 Y4=K21+K22+K23+K24+K25+K26
970 X7=(Y1+Y2+Y3)*X1
980 X8=(K26+K27+K28+K29+K30+K31+K32+K33+K34+K35)*X1+X6+X7
990 !
1000 IF Icalc<1 THEN GOTO 1080
1010 PRINT "          TSVAR INTERNAL PARAMETERS"
1020 PRINT LIN(2), "X6=";X6, "Y1=";Y1
1030 PRINT "Y2=";Y2, "Y3=";Y3
1040 PRINT "Y4=";Y4, "X7=";X7
1050 PRINT "X8=";X8
1060 PRINT "IS 16"
1070 !
1080 ! OBJECTIVE FUNCTION :
1090 Max=(50*Y1+9.583*Y2+20*Y3+15*Y4-852960-38100*(X2+.01*X3)+K31+K32*X2+K33*X3
+K34*X4+K35*X5)*X1-24345+15*X6
1100 Obj=-Max

```

```
1110 !  
1120 ! CONSTRAINTS :  
1130 G(1)=-X6  
1140 G(2)=X6-294000  
1150 G(3)=-X7  
1160 G(4)=X7-294000  
1170 G(5)=-X8  
1180 G(6)=X8-277200  
1190 !  
1200 !  
1210 SUBEND
```

```

100 SUB Analiz(X(*),G(*),Gg(*),C(*),Obj,
110 !
120 !
130 !
140 !
150 !
160 !
170 !
180 !
190 !
200 !
210 !
220 !
230 !
240 !
250 !
260 !
270 !
280 !
290 !
300 !
310 !
320 !
330 !
340 !
350 !
360 !
370 !
380 !
390 !
400 !
410 !
420 !
430 !
440 SUBEND

      "I7VAR"

      A CONSTRAINED OPTIMIZATION PROBLEM

      Kuester, J. L., and Mize, J. H., Optimization Techniques,
      McGraw Hill, San Francisco 1973, pp.73-74.

      A TEST PROGRAM FOR OPTIMIZER DEVELOPEMENT.
      HDV = 7
      NCON = 1
      SIDE CONSTRAINTS: ALL X(I) > 0
      IFUE MINIMUM = -200

      -----

      ! NOTE : SIDE CONSTRAINTS ENTERED ON INPUT, ALL X(I) > 0

      ! DESIGN VARIABLES :
      X1=X(1)
      X2=X(2)
      X3=X(3)
      X4=X(4)
      X5=X(5)
      X6=X(6)
      X7=X(7)
      ! OBJECTIVE FUNCTION :
      Obj=-60*X1-60*X2-40*X3-10*X4-20*X5-10*X6-3*X7
      ! CONSTRAINTS :
      G(1)=-10+3*X1+5*X2+4*X3+1*X4+4*X5+3*X6+1*X7
      ! SIDE CONSTRAINTS : TO BE ENTERED ON INPUT
      ! ALL X(I) >= 0

```

APPENDIX G

NISCO Subprogram Listing

Below is a cross reference list of major equations used in the NISCO program to the references used to develop the equations.

<u>Reference Number</u>	<u>NISCO Subprogram Line Number</u>
3.	820 - 850
4.	1085 - 1090
5.	915, 985 - 1045
6.	855, 925, 930, 965 - 980, 1100, 1180 - 1210, 1255 - 1345, 1460, 1465,
11.	905, 1115, 1125, 1145
12.	1445 - 1455, 1470 - 1480
13.	1600 - 1605

```

100 SUB 'inaliz(X(*),G(*),Gg(*),C(*),Obj)
105 !
110 ! *****
115 ! * *****
120 ! * *****
125 ! * *****
130 ! * *****
135 ! * *****
140 ! * *****
145 ! * *****
150 ! * *****
155 ! * *****
160 ! * *****
165 ! * *****
170 ! *****
175 ! *****
180 DIM Ds(13),Nhld(13),Ib(13,10),Alts(13,10),Azms(13,10),Tamb(13),Drf(13)
185 !
190 Icalc=C(1)
195 Pi=3.141592654
200 Ncal=Ncal+1
205 Thetai=X(1)*PI/180
210 Thetat=X(2)*PI/180
215 R=X(3)/12
220 L=X(4)
225 Mfr=X(5)
230 !
235 !
240 N1: !
245 ! ----- CONSTANTS -----
250 Lat=40*PI/180
255 Awall=0
260 Alpr=.93
265 Eptr=.40
270 Rhor=.07
275 Rhom=.89
280 !
! 40 DEGREES NORTH LATITUDE
! WALL AZIMUTH ANGLE w/r TO SOUTH
! RECEIVER ABSORPTIVITY (OXIDIZED Cu)
! RECEIVER EMISSIVITY (THERMAL RAD.)
! RECEIVER REFLECTIVITY
! REFLECTOR REFLECTIVITY (VACUUM
! DEPOSITED Al ON RESIN)

```

```

285 ALPAB=.03      ! COVER AVERAGE ABSORPTANCE
290 TAUB=.8       ! COVER AVERAGE TRANSMITTANCE
295 RHOG=.17      ! COVER AVERAGE REFLECTIVITY
300 SBC=1.714E-9  ! STEPHAN BOLTZMAN CONSTANT
305              ! ( BTU/Hr Ft2 R4 )
310 GC=32.2      ! GRAVITY CONSTANT
315 EPTA=.94      ! COVER EMISSIVITY (THERMAL RAD.)
320 VP=3          ! VAPOR PRESSURE (mm Hg)
325 A3=.68       ! LATITUDE FUNCTION
330 CC=0          ! CLOUD COVER (TENTHS)
335 RHAB=.07      ! COVER AVERAGE REFLECTIVITY
340 TCI=100       ! COOLANT INLET TEMP TO RECEIVER (F)
345 SG=.87       ! COOLANT SPECIFIC GRAVITY
350 ZZZ=1        ! ITERATION COUNTER
355 IPRINT=7      ! PRINTER CONTROL
360 DT=.0001      ! CONVERGENCE CRITERIA (inchm/100)
365 NYRS=20       ! NUMBER OF YEARS
370 CAC=22.5      ! COLLECTOR COST ( $/ft2 )
375 CF=8.14E-6   ! FUEL COST ( $/Btu ) FOR GAS
380 LA=.1         ! ANNUAL INFLATION RATE
385 IF=.11        ! ANNUAL FUEL INFLATION RATE
390 DTCM=10       ! MINIMUM CHANGE IN COOLANT TEMP
395              !
400              !
405 N2:          ! ----- DATA -----
410              !
415              ! D3(M) - SOLAR DECLINATION (MONTH)
420 DATA -0.34907,-.188496,0.,.20246,0.349066,0.409279,.35954,0.214675,0.,-.1832
425 6.,-.345575,-.409279
430              ! RHID(M) - NUMBER OF SOLAR INSOLATION HOUR PERIODS / DAY (MONTH)
435 DATA 5,6,6,7,8,8,8,8,7,6,5,5
440              ! IB(M,H) - TOTAL INSOLATION ON NORMAL SURFACE (MONTH,HOUR) (BTU/Ft2)
445

```

! DATA FOR 40 deg NORTH LATITUDE FROM ASHRAE HANDBOOK OF FUNDAMENTALS

436	DATA 294,289,274,239,142	! JAN. 21
440	DATA 308,305,295,274,224,69	! FEB. 21
445	DATA 307,305,297,282,250,171	! MAR. 21
455	DATA 293,292,286,274,252,206,89	! APR. 21
460	DATA 284,283,277,267,250,216,144,1	! MAY 21
465	DATA 279,277,272,263,246,216,155,22	! JUN. 21
470	DATA 276,275,269,259,241,208,138,2	! JUL. 21
475	DATA 280,278,272,260,237,191,61	! AUG. 21
480	DATA 290,287,280,263,230,149	! SEP. 21
485	DATA 294,291,280,257,204,48	! OCT. 21
490	DATA 288,283,268,232,136	! NOV. 21
495	DATA 285,280,261,217,89	! DEC. 21
500	! ALT(N,H) - SOLAR ALTITUDE (MONTH,HOUR)	
505	DATA 30,28.4,23.8,16.8,8.1	! JAN. 21
510	DATA 40,38.1,32.8,25.15.4,4.8	! FEB. 21
515	DATA 50,47.7,41.6,32.8,22.5,11.4	! MAR. 21
520	DATA 61.6,58.7,51.2,41.3,30.3,18.9,7.4	! APR. 21
525	DATA 70,66.2,57.5,46.8,35.4,24.0,12.7,1.9	! MAY 21
530	DATA 73.5,69.2,59.8,48.8,37.4,26.0,14.8,4.2	! JUN. 21
535	DATA 70.6,66.7,57.9,47.2,35.8,24.3,13.1,2.3	! JUL. 21
540	DATA 62.3,59.3,51.7,41.8,30.7,19.3,7.9	! AUG. 21
545	DATA 50.0,47.7,41.6,32.8,22.5,11.4	! SEP. 21
550	DATA 39.5,37.6,32.4,24.5,15.0,4.5	! OCT. 21
555	DATA 30.2,28.6,24.0,17.0,8.2	! NOV. 21
560	DATA 26.6,25.0,20.7,14.0,5.5	! DEC. 21
565	! AZIM(N,H) - SOLAR AZIMUTH ANGLE (MONTH,HOUR)	
570	DATA 0,16,30.9,44,55.3	! JAN. 21
575	DATA 0,18.9,35.9,50.2,62.2,72.7	! FEB. 21
580	DATA 0,22.6,41.9,57.3,69.6,80.2	! MAR. 21
585	DATA 0,29.2,51.4,67.2,79.3,89.5,98.9	! APR. 21
590	DATA 0,37.1,60.9,76.0,87.2,96.6,105.6,114.7	! MAY 21
595	DATA 0,41.9,65.8,80.2,90.7,99.7,108.4,117.3	! JUN. 21
600	DATA 0,37.9,61.7,76.7,87.8,97.2,106.1,115.2	! JUL. 21
605	DATA 0,29.7,52.1,67.9,79.9,90.9,99.5	! AUG. 21
610	DATA 0,22.6,41.9,57.3,69.6,80.2	! SEP. 21
615	DATA 0,18.7,35.6,49.8,61.9,72.3	! OCT. 21
620	DATA 0,16.1,31.0,44.1,55.4	! NOV. 21
625	DATA 0,15.2,29.4,41.9,53	! DEC. 21

```

630 ! Tamb(M) - AVERAGE DAILY TEMPERATURE (MONTH)
635 DATA 40,40,45,55,60,70,80,80,80,70,60,45,40
640 ! Drf(M) - DIFFUSE SOLAR RADIATION FACTOR (MONTH)
645 DATA 0.058,0.06,0.071,.097,.121,.134,.136,.122,.092,.073,.063,.057
650 ! READ INPUT DATA
655 FOR M=1 TO 12
660 READ D=(M)
665 NEXT M
670 FOR M=1 TO 12
675 READ Nhid(M)
680 NEXT M
685 FOR M=1 TO 12
690 FOR H=1 TO Nhid(M)
695 READ Ib(M,H)
700 NEXT H
705 NEXT M
710 FOR M=1 TO 12
715 FOR H=1 TO Nhid(M)
720 READ Altsd
725 Alts(M,H)=Altsd*PI/180
730 NEXT H
735 NEXT M
740 FOR M=1 TO 12
745 FOR H=1 TO Nhid(M)
750 READ Azmd
755 Azm(M,H)=Azmd*PI/180
760 NEXT H
765 NEXT M
770 FOR M=1 TO 12
775 READ Tamb(M)
780 NEXT M
785 FOR M=1 TO 12
790 READ Drf(M)
795 NEXT M
800 !

```

! CHANGE TO RADIANS


```

805 1 ----- COLLECTOR GEOMETRY -----
810 N3: 1
815 1
820  $T = R * (\text{Theta} + \text{Theta} + \text{PI} / 2 - \text{COS}(\text{Theta} - \text{Theta})) * (1 + \text{SIN}(\text{Theta} - \text{Theta}))$ 
825  $\text{Theta} = 3 * \text{PI} / 2 - \text{Theta}$  ! THETA MAX.
830  $\text{Theta} = \text{PI} / 2 + \text{Theta}$  ! THETA MIN.
835  $R = 2 * (1 + \text{SIN}(\text{Theta} - \text{Theta})) - 1 + \text{SIN}(\text{Theta} + \text{PI} / 2)$  ! APERTURE OPENING AREA
840  $R = 2 * \text{PI} - \text{P}$  ! RECEIVER AREA
845  $C = R / R$  ! CONCENTRATION RATIO
850  $C = -\text{P} + \text{COS}(\text{Theta} + 1 + \text{COS}(\text{Theta} + \text{PI} / 2))$  ! COLLECTOR DEPTH (ft.)
855  $\text{Hbar} = \text{LOG}(C / C \wedge .5)$  ! AVERAGE NUMBER OF REFLECTIONS
860 1
865  $\text{Tr} = 150$  ! ASSUME AN INITIAL RECEIVER TEMP
870  $\text{Ta} = 100$  ! ASSUME AN INITIAL COVER TEMP
875 1
880 1
885 N4: 1 ----- MONTHLY CALCULATIONS -----
890 1
895 1
900 FOR M=1 TO 12
905  $\text{Beta} = \text{Theta} - \text{Alts}(M, 1) + \text{PI} / 2$  ! COLLECTOR TILT ANGLE
910  $\text{Beta} = \text{PI} / 2 - \text{Beta} - \text{Theta}$  ! MINIMUM ACCEPTED SOLAR ALTITUDE
915  $\text{F} = (1 - \text{COS}(\text{Beta})) / 2$  ! GROUND ANGLE FACTOR
920 ! SKY HEAT LOSS CONSTANTS
925  $\text{As} = \text{Epta} - \text{Sbc} + (\text{Tamb}(M) + 460) * .4 * (.39 - .009C + "P") * (1 - R3 + C) - 4 * \text{Ept} + \text{Sbc} * (\text{Tamb}(M) + 460) \wedge .4$ 
930  $\text{Bs} = 4 * \text{Epta} - \text{Sbc} * (\text{Tamb}(M) + 460) \wedge .3$ 
935 1
940 N5: 1 ----- HOURLY CALCULATIONS -----
945 1
950 FOR H=1 TO HHID(M)
955  $\text{Hs} = (H - 1) * 15 + \text{PI} / 180$  ! SOLAR HOUR ANGLE
960 !  $\text{Csi} = \text{COSINE OF THE ANGLE THE SUN MAKES WITH THE COVER NORMAL}$ 
965  $\text{Csi} = \text{SIN}(\text{Ds}(M)) * (\text{SIN}(\text{Lat}) * \text{COS}(\text{Beta}) - \text{COS}(\text{Lat}) * \text{SIN}(\text{Beta}) * \text{COS}(\text{Hwall}))$ 
970  $\text{Csi} = \text{COS}(\text{Ds}(M)) * (\text{COS}(\text{Lat}) * \text{COS}(\text{Beta}) + \text{SIN}(\text{Lat}) * \text{SIN}(\text{Beta}) * \text{COS}(\text{Hwall}))$ 
975  $\text{Csi} = \text{COS}(\text{Ds}(M)) * \text{SIN}(\text{Beta}) * \text{SIN}(\text{Hwall}) * \text{SIN}(\text{H})$ 
980  $\text{Csi} = \text{Csi} + \text{Csi}2 + \text{Csi}3$ 
985 !  $\text{Hpcr} = \text{PERCENTAGE OF A PARTIAL HOUR OF RADIATION}$ 

```

```

990 Hpcr=(Alc*(M,H-1)-Betag)/Al=(M,H-1)-Al*(M,H-1)
995 ! Ibc - DIRECT BEAM RADIATION INCIDENT ON THE COVER
1000 Ibc=Ib*(M,H)*Cai
1005 IF Alts(M,H)<Betag THEN Ibc=Ibc+Hpcr
1010 ! Idc - DIFFUSE BEAM RADIATION INCIDENT ON THE COVER
1015 Idc=Drf*(M)*Ibc*(1-Feg)
1020 ! Irc - REFLECTED BEAM RADIATION INCIDENT ON THE COVER
1025 Irc=Ibc*(Drf*(M)+SIN(Alc*(M,H))*Phog+Feg)
1030 ! Tauai - COVER TRANSMISSIVITY AS A FUNCTION OF INCIDENT ANGLE
1035 Tauai=-.008895+2.71235*Cai-.62062+Cai*2-7.07329+Cai*3+9.75995-Cai*4-3.89922
+Cal*5
1040 ! Alpai - COVER ABSORPTANCE AS A FUNCTION OF INCIDENT ANGLE
1045 Alpai=.01154+.77674*Cai-3.94651*Cai*2+8.57391+Cai*3-9.38139+Cai*4+3.01188+
Cai*5
1050 Zzz=1
1055 ! ITERATION COUNTER
1060 Hc=1
1065 ! PERFORM A HEAT BALANCE ON THE COLLECTOR ----
1070 Zzz=Zzz+1
1075 Tr=Tr+460
1080 Tar=Ta+460
1085 Cp=4.94E-4*Tr+.4036
1090 Visc=(-.053*Tr+32.3)*6.71955E-4
1095 ! CALCULATE THE HEAT TRANSFER COEFFICIENTS.
1100 ! Hcar - RADIATION HEAT TRANSFER COEFFICIENT : COVER TO RECEIVER
1105 Hcar=Sbc*(Tr+Tar)*(Tr*2+Tar*2)/(1.Epr+1.Epta-1)
1110 ! Hcra - CONVECTION HEAT TRANSFER COEFFICIENT : RECEIVER TO COVER
1115 Hcra=.27*(ABS(Tr-Ta)/(2*Ar))*.25
1120 ! Hcar - CONVECTION HEAT TRANSFER COEFFICIENT : COVER TO RECEIVER
1125 Hcar=.29*(ABS(Ta-Tr)/2*SIN(Beta)/Ar)*.25
1130 ! Hcb - AVERAGE HEAT TRANSFER COEFFICIENT BETWEEN COVER AND RECEIVER
1135 Hcb=(Hcra+Hcar)/(Cr*(Hcar+Hcra/Cr))
1140 ! Hce - CONVECTION HEAT TRANSFER COEFFICIENT COVER TO ENVIRONMENT
1145 Hce=.29*(ABS(Ta-Tamb*(M))*SIN(Beta)/Ar)*.25+Cr

```

```

1150 ! -----
1155 N7: ! ---- PERFORM A HEAT BALANCE ON THE COVER AND SOLVE FOR TA ----
1160 ! -----
1165 !
1170 ! Qba - DIRECT SOLAR RADIATION ABSORBED BY THE COVER BOTH DIRECTLY AND
1175 !       INDIRECTLY AFTER REFLECTION FROM THE RECEIVER
1180 Qba=Ibc*(Alpai+Tauai*Rhom^(2*Nbar)*Rhor*Alpab)*Cr
1185 ! Qda - DIFFUSE SOLAR RADIATION ABSORBED BY THE COVER
1190 Qda=Idc*Alpab*Cr
1195 ! Qra - REFLECTED SOLAR RADIATION ABSORBED BY THE COVER
1200 Qra=Irc*Alpab*Cr
1205 ! Tap - NEW COVER TEMPERATURE
1210 Tap=(Qba+Qda+Qra-Bsky+460+Tr*(Hrar+Hcb)+Hce*Tamb/M)/(Hrar+Hcb+Bsky+H
ce)
1215 IF ABS(Tap>500) THEN Tap=70
1220 ! -----
1225 N8: ! ---- PERFORM A HEAT BALANCE ON THE RECEIVER ----
1230 ! ----- AND SOLVE FOR THE USEFUL HEAT OUT -----
1235 ! -----
1240 !
1245 ! Qbr - DIRECT SOLAR RADIATION ABSORBED BOTH DIRECTLY AND INDIRECTLY
1250 !       BY THE RECEIVER AFTER REFLECTION FROM THE REFLECTOR
1255 Qbr=Ibc*Tauai*Rhom*Nbar*Alpr*(1+Rhom^(2*Nbar)*Rhor*Rhab)*Cr
1260 ! Qdr - DIFFUSE SOLAR RADIATION ABSORBED BY THE RECEIVER
1265 Qdr=Idc*Taub*Rhom*Nbar*Alpr
1270 ! Qrr - REFLECTED SOLAR RADIATION ABSORBED BY THE RECEIVER
1275 Qrr=Irc*Taub*Rhom*Nbar*Alpr
1280 ! Qcra - CONVECTIVE EXCHANGE BETWEEN THE RECEIVER AND THE COVER
1285 Qcra=Hcb*(Tr-Ta)
1290 ! Qir - RADIATIVE EXCHANGE BETWEEN THE RECEIVER AND THE COVER
1295 Qir=Hrar*(Tr-Ta)
1300 ! Qu - USEFUL HEAT EXTRACTION
1305 Qu=(Qbr+Qdr+Qrr-Qcra-Qir)*L*Ar
1310 !

```

```

1315 | -----
1320 N9: | ----- PERFORM A HEAT BALANCE ON THE WORKING FLUID -----
1325 | | ----- AND SOLVE FOR THE NEW RECEIVER TEMP -----
1330 | | -----
1335 | | -----
1340 | Tc2 - COOLANT EXIT TEMPERATURE
1345 Tc2=Qw/(Cp*Mfr)+Tc1
1350 IF (M=6) AND (H=1) THEN Tc2=Tc2
1355 | Trp - NEW RECEIVER TEMPERATURE
1360 Trp=(Tc1+Tc2)/2
1365 IF ABS(Trp)>10000 THEN Trp=10000
1370 | -----
1375 N10: | ----- CHECK FOR CONVERGENCE OF Ta WITH Tap AND Tr WITH Trp -----
1380 | | -----
1385 | | -----
1390 IF (ABS((Ta-Tap)/Tap)<Dt) AND (ABS((Tr-Trp)/Trp)<Dt) THEN GOTO N11
1395 Ta=Tap
1400 Tr=Trp
1405 GOTO N6
1410 | -----
1415 N11: | CONVERGENCE MET
1420 | -----
1425 | -----
1430 N12: | ----- CALCULATE PUMPING POWER REQUIRED -----
1435 | | -----
1440 | | -----
1445 Den=Sg*62.4
1450 Mv=Mfr/(PI*R^2)
1455 Re=Mv*2*R/(Visc*3600)
1460 IF Re<2100 THEN Ff=16/Re
1465 IF Re>=2100 THEN Ff=.079*Re^(-.25)
1470 Vc=Mfr/(Den*PI*R/2*3600)
1475 Dpc=2*Ff*Den*Vc^2/(R*Gc)
1480 Ppc=Sg*Mfr*Dpc*1.84939E-2*L/Den
1485 IF Alts(M,H)<Betag THEN Ppc=Ppc*Hpct

```

```

! COOLANT DENSITY (lbm/ft^3)
! COOLANT MASS VELOCITY (lbm/hr/ft^2)
! REYNOLDS NUMBER
! FRICTION FACTOR
! COOLANT VELOCITY (ft/sec)
! COLLECTOR PUMPING POWER (Btu/hr)

```

```

1490 Qa=Cu-Ppc
1495 IF (M=5) AND (H=1) THEN Qa1=Qa
1500 IF Qa<0 THEN GOTO N14
1505 IF H=1 THEN Qa=2*Qa
1510 ! Qtot = TOTAL USEFUL ENERGY OUT
1515 Qtot=Qtot+Qa
1520 Htot=Htot+(Hhid-1)*2+1
1525 IF A113*(M,H)-Betag THEN GOTO N14
1530 N13: ! -----
! COLLECTOR ENERGY AVAILABLE
! INSTANTANEOUS HEAT GAIN
! WHEN PUMP REQ. Q COLLECTED
! ALLOWS FOR DOUBLE SOLAR PERIOD
! TOTAL NUMBER OF HOURS
! -----
1535 NEXT H
! -----
1540
1545 N14: ! -----
! HEAT M
! -----
1550
1555 ! -----
1560 ! -----
1565 ! -----
1570 N15: ! ----- PERFORM AN ECONOMIC ANALYSIS ON THE SYSTEM -----
1575 ! -----
1580 ! -----
1585 ! -----
1590 Qyr=30*Qtot
1595 Ce=Qyr+Cf
1600 Ir=Ia-Ir-Ia*Ir
1605 Clc=Ce*(1+Ir)^Nyr-1)/(1+Ir)^Nyr
1610 Ci=Cac*L*(.8*At+.2*Cd)
1615 Ctot=Ci-Clc
1620 IF Qyr=0 THEN Qyr=1E-10
1625 Obj=Ctot-(Qyr+Nyr)*1E6
1630 !
! YEARLY HEAT GAIN
! FIRST YEAR FUEL SAVINGS
! EQUIVALENT ANNUAL INTEREST RATE
! INITIAL COST / #.yr^3 / COLLECTOR
! TOTAL COST / -COST PEP. SAVINGS

```

```

1635 ! -----
1640 N16: ! ----- CONSTRAINTS -----
1645 ! -----
1650 ! -----
1655 Q1=50000
1660 G(1)=Theta1-Theta1-3*PI/2 ! MAXIMUM THETA-T
1665 G(2)=Theta1+PI/2-Theta1 ! MINIMUM THETA-T
1670 G(3)=- (Mfr-1)*10
1675 G(4)=- (X(3)-.1)*10
1680 G(5)=1-Qtot/(2*Q1) ! MINIMUM AVERAGE DAILY HEAT GAIN
1685 G(6)=Tc21-600 ! MAXIMUM COLLECTOR TEMPERATURE
1690 IF Icalc=2 THEN GOTO N18
1695 ! -----
1700 N17: ! ----- OUTPUT -----
1705 ! -----
1710 PRINTER IS 0
1715 IF Icalc=1 THEN PRINT "INITIAL DESIGN:"
1720 IF Icalc=3 THEN PRINT "FINAL DESIGN:"
1725 PRINT "FOR ";Q1;" BTU/DA' SOLAR COLLECTOR"
1730 PRINT "DESIGN VARIABLES:"
1735 PRINT "INCIDENT ACCEPTANCE ANGLE = ";X(1);" DEGREES"
1740 PRINT "TRUNCATION ANGLE = ";X(2);" DEGREES"
1745 PRINT "RECEIVER RADIUS = ";X(3);" INCHES"
1750 PRINT "COLLECTOR LENGTH = ";X(4);" FEET"
1755 PRINT "COOLANT MASS FLOW RATE = ";X(5);" Lbm/Hr"
1760 PRINT "DESIGN FEATURES:"
1765 PRINT "CONCENTRATION RATIO = ";Cr
1770 PRINT "COLLECTOR APERTURE AREA = ";At*L;" Ft^2"
1775 PRINT "COLLECTOR DEPTH = ";Cd*12;" INCHES"
1780 PRINT "COOLANT VELOCITY = ";Vc;" Ft/Sec"
1785 PRINT "MAXIMUM COOLANT TEMPERATURE = ";Tc21;" DEG F"
1790 PRINT "INSTANTANEOUS COLLECTOR EFFICIENCY = ";Qai/(At*L*279)
1795 PRINT "AVERAGE DAILY HEAT GAIN = ";Qtot/2;" Btu"
1800 PRINT "FIRST YEAR FUEL SAVINGS = $";Ce
1805 PRINT "LIFE CYCLE FUEL SAVINGS = $";C1c
1810 PRINT "INITIAL COST = $";Ci
1815 PRINT "TOTAL LIFE CYCLE COST/ 1E6 Btu = $";Obj
1820 N18: ! END
1825 SUBEND

```

APPENDIX H
Sample DESOP Output

Appendix H is a sample computer output for the DESOP program.

ANALYZE PROGRAM : ROSEN

OPTIMIZER USED : DESOP

INPUT FOR OPTIMIZATION :

```

      NBY= 4      NCON= 3      IPRINT= 5      DELFUN= .001
      DAEFUN= .001      ITMAX= 20      ICHDIR= 5      FDCH= .0001
      FDCHM= .0001      ABOSJ1= .1      ALPHA= .1      IPDEG= 0
      CT= .1      CTMIN=-.004      CTL= .1      CTLMIN=-.001
      PHI= 5      THETA= 1      ITRM= 3      CG= 0
      NCF= 0      IRMAX= 10      PZ= 2      RMULT= 2
      EXPG= 1.5      NSCAL= 1

      X( 1 ) = 1      X( 2 ) = 1      X( 3 ) = 1      X( 4 ) = 1

      VLB(1) = -1.000000000000E+50      VUB(1) = 1.000000000000E+50
      VLB(2) = -1.000000000000E+50      VUB(2) = 1.000000000000E+50
      VLB(3) = -1.000000000000E+50      VUB(3) = 1.000000000000E+50
      VLB(4) = -1.000000000000E+50      VUB(4) = 1.000000000000E+50

```


INITIAL DESIGN

DESIGN VARIABLES :

$X(1) = 1$

$X(2) = 1$

$X(3) = 1$

$X(4) = 1$

CONSTRAINTS :

$G(1) = -4$

$G(2) = -6$

$G(3) = -1$

OBJECTIVE FUNCTION :

$OBJ = 31$

$OBJA = 31$

OPTIMIZATION RESULTS

FINAL DESIGN VARIABLES :
X(1) = -5.16678781285E-03
X(3) = 1.99950170832

X(2) = 1.01911957463
X(4) = -.995109574088

FINAL CONSTRAINTS :

G(1) = -.00279456917 G(2) = -.9439983936 G(3) = .00232056596

FINAL OBJECTIVE FUNCTION :

OBJ = 6.006979126 OBJR = 5.999024765

NUMBER OF ITERATIONS : 28

NUMBER OF TIMES ANALYZE CALLED :

306

PC HAS BEEN INCREASED 5 TIMES TO 64

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